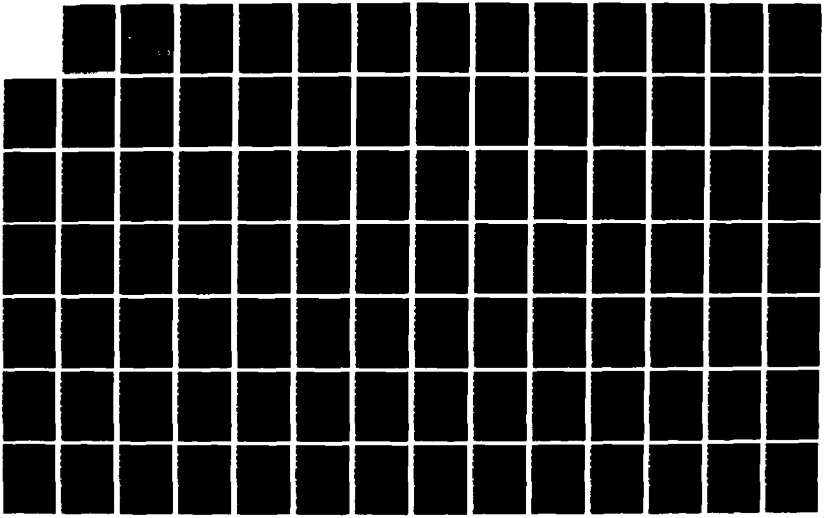
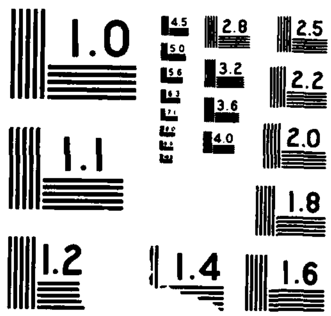
AD-A192 502 MITIGATION OF MAINS DISTURBANCES(U) PENNSYLVANIA STATE 1/3
UNIV UNIVERSITY PARK R STANDLER ET AL NOV 87
AFWL-TR-86-80 F29601-85-K-0035

UNCLASSIFIED F/G 10/2 NL




1.0
1.1
1.2
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6

AFWL-TR-86-80

AFWL-TR-
86-80

(2)

DTIC FILE COPY

AD-A192 502

MITIGATION OF MAINS DISTURBANCES

R. B. Standler
A. C. Canike

Pennsylvania State University
University Park, PA 16802

November 1987

Final Report

Approved for public release; distribution unlimited.

AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117-6008

This final report was prepared by Pennsylvania State University, University Park, Pennsylvania under Contract F29601-85-K-0035, Job Order 88092604 with the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico. Mr David H. Hilland (NTA) was the Laboratory Project Officer-in-Charge.

This technical report has been reviewed and is approved for publication.

David H. Hilland

DAVID H. HILLAND
Project Officer

Kenneth N. Cole

KENNETH N. COLE
Captain, USAF
Chief, Technology Branch

FOR THE COMMANDER

Philip J. Messuri

PHILIP J. MESSURI
Lieutenant Colonel, USAF
Chief, Aircraft & Missiles Division

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

A192502

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b DECLASSIFICATION/DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFWL-TR-86-80
6a NAME OF PERFORMING ORGANIZATION The Pennsylvania State University 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Air Force Weapons Laboratory
6c ADDRESS (City, State and ZIP Code) University Park, PA 16802	7b. ADDRESS (City, State and ZIP Code) Kirtland Air Force Base, NM 87117-6008
8a NAME OF FUNDING/SPONSORING ORGANIZATION 8b OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F29601-85-K-0035
8c ADDRESS (City, State and ZIP Code)	10 SOURCE OF FUNDING NOS PROGRAM ELEMENT NO. 62601F; PROJECT NO. 8809; TASK NO. 26; WORK UNIT NO. 04
11 TITLE (Include Security Classification) MITIGATION OF MAINS DISTURBANCES	

12. PERSONAL AUTHOR(S)
Standler, Dr Ronald B.; and Canike, A.C.

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Final	FROM Apr 85 TO Jun 86	1987, November	198

16 SUPPLEMENTARY NOTATION

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB GR	Line conditioner, Transient suppression, Uninterruptable power supply, Computer protection, Electromagnetic transient, Overvoltage, Power surge

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

This report discusses the use and performance of line conditioners and uninterruptible power supplies (UPSs). The devices studied are for use on single phase, 120 V rms, 60 Hz service for maximum loads between 400 VA and 550 VA. Data are presented for both dynamic and static line and load regulation, turn-on and turn-off behavior, and response to four different high voltage transient waveforms on the input. It is recommended that metal-oxide varistors be connected upstream from any kind of line conditioner. The special problems of using line conditioners and UPSs with desktop computer systems are discussed.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS ☐	21 ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a NAME OF RESPONSIBLE INDIVIDUAL Mr Dave Hilland	22b TELEPHONE NUMBER (Include Area Code) (505) 844-9758 22c OFFICE SYMBOL NTA

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

ACKNOWLEDGMENTS

Mr. William Burkhard loaned a Tektronix 7854 oscilloscope mainframe to us for compensation of our voltage probes and 7A13 amplifiers. He also loaned a Hewlett Packard model 9836 computer to us for the tests described in Section 6.

Professor David Landis loaned us an IBM PC/XT for the tests described in Section 6.

Mr. David Hilland of AFWL was the technical contract officer for this research project. We thank him for arranging the financial support of this project.

CONTENTS

CONTENTS (CONTINUED)

CONTENTS (CONCLUDED)

SECTION 1

Modern electronic equipment, including desktop computers, is vulnerable to both damage and upset by disturbances on the mains that supply electric power to the equipment. This section reviews the types and causes of common disturbances. An uncommon cause of disturbance, which is of great significance, is the high-altitude electromagnetic pulse (HEMP) that illuminates overhead power lines. In addition, source region EMP from ground bursts of nuclear weapons can cause severe transient overvoltages to propagate away from the region affected by blast and thermal damage.

Nonlinear components and circuits for protection of electronic equipment from damage or upset by transient overvoltages are reviewed in Reference 1. The present report contains more detailed information about devices for protecting equipment that is connected to single phase, 120 V rms, 60 Hz mains.

The normal potential difference between the hot and neutral conductors at a wall outlet is a sinusoidal waveform with a nominal amplitude of 120 V rms. ("Rms" means "root-mean-square" and is a way of measuring a continuously varying waveform. A 120 V rms waveform produces the same heating of a resistive load as a constant 120 V potential difference.)

The rms voltage available at a wall outlet can vary and still be acceptable. American National Standard Institute (ANSI) document C84.1 sets the standard for acceptable steady-state rms voltage values. Most of the time the line is to provide between 108 V rms and 125 V rms (90% to +104% of nominal). Infrequently, the line may have excursions to as low as 104 V rms or as high as 127 V rms (87% to 106% of nominal) and still be considered acceptable by the utility.

Mains voltages that are acceptable according to the ANSI standard permit proper operation of most electrical loads. However, certain sensitive equipment may not operate over the full range of "acceptable" line voltages. Common examples of sensitive equipment include computer systems and electronic instruments. Sensitive equipment requires a narrower range of acceptable line voltages. One proposal is that the mains potential be between 110 V rms and 125 V rms (Ref. 2). Goldstein and Speranza (Ref. 3) suggested that the mains voltage be between 115 V rms and 125 V rms for computer sites.

DEFINITIONS OF MAINS DISTURBANCES

There are several ways that disturbances on the power line can adversely affect electronic equipment:

1. Reduction in rms voltage below acceptable values (e.g., less than 90% of nominal) of more than 8 ms duration is called a "sag" if it lasts no more than a few seconds, or a "brownout" if it has a duration of minutes to hours.
2. Temporary loss of the mains is called a "flicker" if it lasts less than a second, or an "outage" or "blackout" if it lasts for a longer interval.
3. High-voltage pulses of less than 8 ms duration superimposed on the power line voltage are called "transient overvoltages," "impulses," or "spikes," or sometimes "surges".
4. Increases in rms voltage of more than 8 ms duration are called "surges".
5. High-frequency noise on the mains is known as "radio-frequency interference" (RFI) or "electromagnetic interference" (EMI).
6. Changes in frequency of the mains waveform are another kind of disturbance.

Sags, flicker, transient overvoltage, surge, and noise are all illustrated in Fig. 1. Figure 1 is an illustration that supports the definitions in this section. It is not intended as a representation of an actual sequence of events on the mains. We now discuss how each of these disturbances can be created.

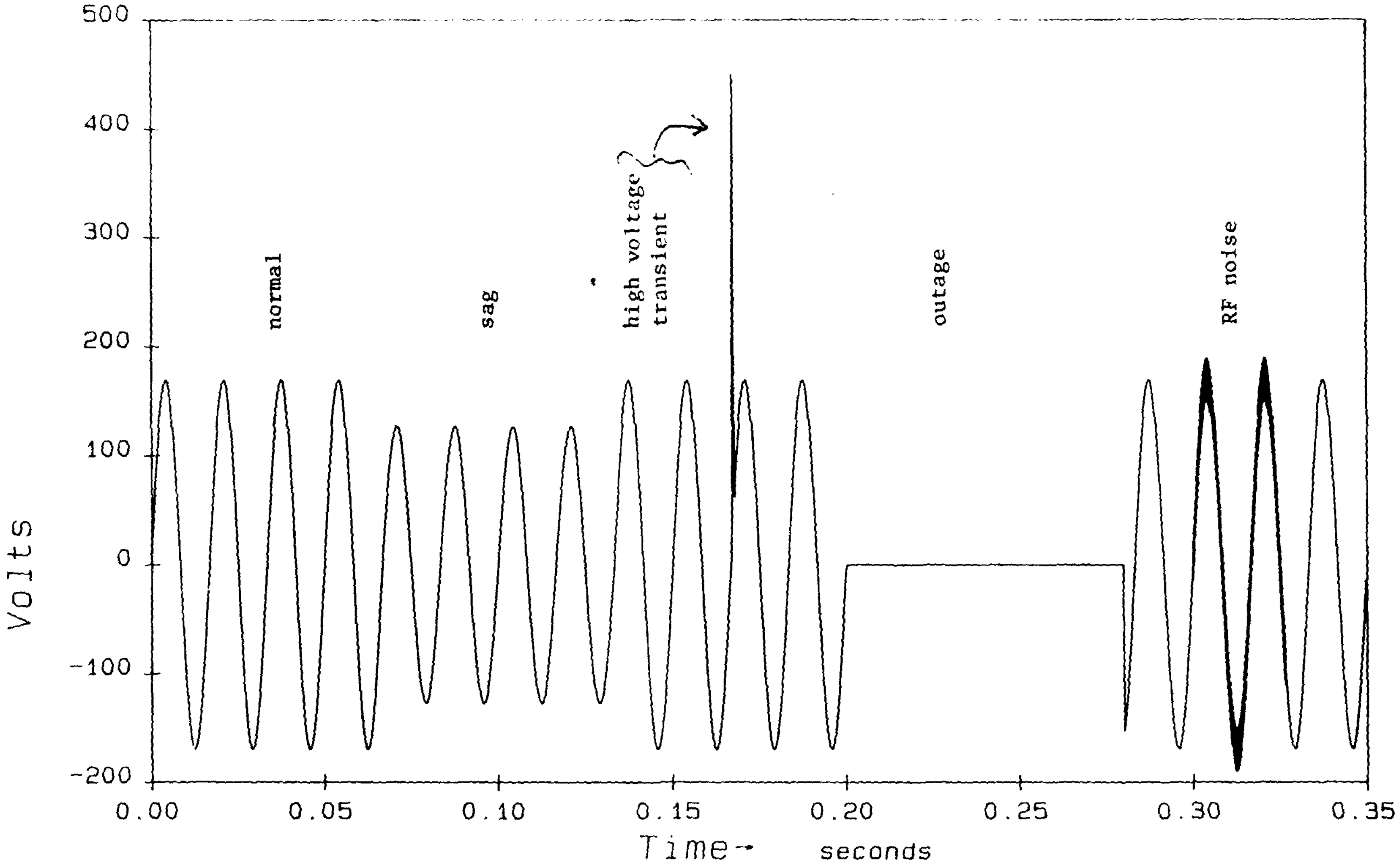


Figure 1. Disturbances on mains.

REDUCTIONS IN RMS LINE VOLTAGE ("SAGS", BROWNOUTS)

The voltage at the wall outlet can be less than the nominal value for any of several different reasons. There may be a loss of voltage due to resistance of wires, fuses or circuit breakers, and connectors. When a large motor (e.g., in a refrigerator, washing machine, etc.) is switched on, the mains voltage decreases for a fraction of a second. When a motor starts, it draws a larger-than-usual current that produces a lower-than-usual voltage, owing to resistance in the wires that connect the motor to the power line. Tungsten filament lamps briefly dim during this "sag." While the dimming of electric lamps may be the only symptom that is easily detected by people, it is not a sensitive indicator. The thermal capacity of the tungsten filament allows the luminosity to decrease slowly when the input power is temporarily lost. Moreover, the persistence of human vision averages luminosity over a period of about 10 ms.

Goldstein and Speranza (Ref. 3) found that sites with a greater incidence of lightning had more sags. Lightning causes arcs between the line and earth which short the generator. These arcs are interrupted by automatically reclosing circuit breakers. During the arc but before the breaker opens, the entire distribution system has a sag or momentary outage. When the breaker opens, the line downstream from the breaker continues to have a momentary outage.

Sometimes the demand for electric power exceeds the available generating capacity. This happens when electric air conditioners are used during hot summer days or when electric heaters are used during cold winter days. The power line voltage may be between 90 and 110 V rms during this condition, which is known as a "brownout." Many computers will not operate properly during brownouts.

Key (Ref. 4) found that, while computers had unpredictable responses to transient overvoltages, "every recorded severe sag was found to disturb the computers." Speranza (Ref. 5) also reported that sags caused computers to malfunction immediately. He found that when the rms voltage dropped below 96 V for as little as 16 ms, computers failed. Kania et al. (Ref. 6) state that large mainframe computers will shut down during a sag to 80% of nominal line voltage that persists for 33 ms or more.

TEMPORARY LOSS OF POWER

Temporary loss of power can be caused by short circuits in the power distribution system (e.g., tree branches blown across overhead power lines, arcs started by lightning strikes, etc.). These faults are isolated by circuit breakers or fuses, but until the breaker trips or the fuse blows, the power line voltage is near zero. Momentary loss of power line may cause electric lights to flicker.

Temporary loss of power can also be caused by breaking of the wires (e.g., automobile hits power pole, ice causes wires to stretch and break) or failure of generators or transformers.

Computers require continuous power to maintain their programs and data in semiconductor memory. When the power is interrupted, data and programs in semiconductor memory are lost. If this information was not previously stored in nonvolatile memory (such as a magnetic disk or bubble memory), then the information is irretrievably lost. To recover from this disaster, the operator must reload the information from a backup copy (or retype it). While loss of power is a rare event, it can be devastating to a computer system.

Kania et al. (Ref. 6) state that large mainframe computers will shut down if they are without power for more than 20 ms.

HIGH-VOLTAGE TRANSIENTS

When inductive loads are switched off or when lighting strikes overhead power lines, high-voltage transients are injected into the power line. Switching of inductive loads may be the most common cause of high voltage transients.

The phenomena of switching off an inductive load can be demonstrated by operating a vacuum cleaner in a darkened room and pulling the plug from the wall outlet while the motor is running. When the plug is pulled from the wall outlet, an arc will be visible at the outlet. (This demonstration may leave a permanent burn mark on the plastic insulation at the outlet.)

A lightning strike raises the potential of the earth ground at the point of the strike by injecting a large current into ground, which is a nonperfect conductor. The increase in potential of earth appears on the power line as a common-mode voltage.

An additional cause of transient overvoltages is the switching of capacitor banks across the power line to correct for power factor caused by inductive loads. Key (Ref. 4) studied a computer site that was experiencing frequent computer failures that were due to this cause.

Common transients have peak voltages with a magnitude between about 200 and 1000 V. Peak voltages up to about 6000 V are possible. Peak voltages larger than 6000 V are limited by breakdown of insulation at wall outlets.

These high-voltage transients can damage semiconductors in electronic power supplies and damage insulation in transformers. Transients that propagate through electronic power supplies can alter memory in computers, produce an error, or even cause the computer to "crash."

SURGE

There are two common meanings for the word "surge": (1) high-voltage transients that have a duration of less than 8 ms, and (2) increases in rms voltage above 106% of nominal for a duration between about 8 ms and a few seconds. The use of one word to describe two different phenomena leads to confusion in the literature. This report uses "surge" to denote increases in the rms voltage for brief durations.

Surges are commonly created when a large load is switched off. Because the generator and distribution system have a small, positive output resistance, the sudden decrease in rms current causes the rms voltage to increase. The rms voltage returns toward normal as voltage regulating equipment in the distribution system responds.

HIGH-FREQUENCY NOISE

High-frequency noise is generally a periodic or repetitive phenomenon, unlike the other disturbances that are discussed above.

High-frequency noise can be injected into the power line by radar, radio, or television transmitters near overhead power lines. Motors can be a potent sources of high-frequency noise due to the sparks from their brushes. Some older computers, video games, and other electronic devices can inject pulses into the power line. Newer equipment must conform to FCC regulations that limit the output of radio-frequency noise from electronic devices.

High-frequency noise can interfere with communications (e.g., disturb radio or television reception) and can also interfere with the normal operation of computers and other sophisticated electronic equipment. The mechanism of interference often involves the power cord as an antenna for the electromagnetic radiation.

CHANGES IN FREQUENCY

The frequency of the line voltage is regulated by utility companies in North America to be 60 Hz. This stable value is necessary to maintain the power grid, the interconnection of different utility systems. As a consequence of the stable frequency, electric clocks can determine the time from the frequency of AC power. (Analog clocks commonly contain a synchronous motor that has a rotation rate that is proportional to the frequency of the AC power. Digital clocks that operate from AC power commonly count cycles of AC power.)

Computer terminals that contain a cathode-ray tube (CRT) display may be sensitive to frequency, since the sweep rate is sometimes derived from the power line frequency. A tolerance of T1 Hz for permissible frequency variations in power for computers is specified by Duell and Roland (Ref. 2).

Synchronous motors are also used in some disk and tape drives in computer systems (Ref. 4). If the frequency of the AC power were to change, these devices might malfunction.

Key (Ref. 4) states that variation of frequency "is not a common computer power problem." Frequency variations of more than T0.5 Hz accounted for less than 0.1% of all power disturbances reported by Goldstein and Speranza (Ref. 3). When using power from a commercial utility, frequency variations do not appear to be a problem. However, frequency variations would be expected to be more troublesome when using a small local generator than when using utility power.

MONITORING OF POWER LINES

Martzloff and Hahn (Ref. 7) were the first to perform a large-scale study of transients on 120 V rms mains. They used a specially-modified Tektronix 515 oscilloscope with a camera that contained 100 feet of 35 mm film. The film automatically advanced after each sweep or after a one-hour exposure, whichever came first. The oscilloscope was set to trigger on waveforms of either polarity with a level greater than 300 V.

They found that transient overvoltages were caused by common appliances, such as fluorescent lamps or an electric motor in a water pump, refrigerator, or food mixer. They also found that the electrical ignition of a oil-burning furnace could inject a pulse with an amplitude between 1500 V and 2500 V. These transients occurred at an average rate of 1.4 to 9.6 times per day.

Transients were also associated with lightning. Many transient overvoltages were of unknown origin.

The oscilloscope in Martzloff and Hahn's study completed its sweep in 100 s. No analysis of rise time or waveform was presented, except for duration and type of waveform for the most severe and most frequent transient at each of 21 sites. Most of the transients were damped oscillations with frequencies between 0.1 MHz and 2 MHz. Durations were between 5 s and 30 s.

While data from this oscilloscope was quite valuable, the equipment was expensive and could not be used to gather data from a large number of different geographical sites for statistical analysis. Martzloff and Hahn (Ref. 7) developed a simple instrument to detect transients that had a peak potential greater than 1200 V. The number of transients that exceeded this threshold was recorded on a mechanical counter. First 249 homes were surveyed for transients for 1 to 2 weeks each. Six homes (2.4%) showed repetitive transients. Then, a total of 91 homes were surveyed for transients during an average of 9.3 weeks each. Most homes had no recorded transients. Four homes had one transient overvoltage, two homes had two transients each. If one assumes that transients occur only during the period of the year that the counters were in the homes, the average rate of positive transients that exceeds 1200 V in a home would be 0.2 per year. If one assumes that transients occur randomly at a constant rate throughout the year, the average rate of positive transients that exceeds 1200 V is 0.5 per year. Martzloff and Hahn's best guess is that the number of transients of both polarities that exceeds 1200 V is 1.6 times the numbers of positive transients given above.

Allen and Segall (Ref. 8) undertook a comprehensive monitoring program of 208 and 240 V rms power lines at computer sites. Like Martzloff and Hahn, they also used two different detector systems in their study of transients on the power line. One was a Tektronix 549 storage oscilloscope and a 35 mm camera with a 20 exposure roll of film. The oscilloscope was set to have one sweep at a relatively fast rate, followed by a second sweep at a slower rate. The film was automatically advanced after the second sweep. Three different sets of sweep rates were considered (Ref. 9):

1. First sweep 0.5 s/cm, second sweep 2 ms/cm. This "did not provide sufficient information about the long-term effects of disturbances."
2. First sweep 250 s/cm, second sweep 15 ms/cm.
3. First sweep 1 ms/cm, second sweep 50 ms/cm. This "did not provide sufficient information about the recorded voltage spikes."

This oscilloscope tube had a limited lifetime, the oscilloscope required daily adjustments, and the film was troublesome to develop and analyze. Because of these problems, Allen (Ref. 9) also designed and built a digital transient detector. This detector produced a printed record of the following three types of disturbances:

1. Transients with frequency components in the band from 3 kHz to 30 kHz. Allen (Ref. 9) stated that these transients are "caused by lightning and other noise sources."
2. Transients with frequency components in the band from 0.3 kHz to 3 kHz. Allen (Ref. 9) stated that these transients are often caused by switching of power-factor correction capacitors or network switching.
3. Undervoltages and overvoltages that persist for longer than 8 ms. The line voltage was sent through a 80-Hz low-pass filter to obtain this information. The disturbances were classified in five levels of undervoltage (90%, 80%, 70%, 57%, and 20% of nominal) and one level of overvoltage (more

than 110% of nominal). Duration was measured in 8 ms increments up to 1.65 s.

Allen and Segall reported their results at the 1974 Winter Meeting of the IEEE Power Engineering Society (Ref. 8). Only 3 of 610 transient overvoltages had an amplitude of more than 100% of the steady-state 60 Hz power waveform. Martzloff (personal communication, 1985) suspects that their analog storage oscilloscope had insufficient writing rate to record transient overvoltages. The 30 kHz limit of their digital transient counter was certainly inadequate to detect all transient overvoltages.

Goldstein and Speranza (Ref. 3) and Speranza (Ref. 5) reported results of monitoring power disturbances at 24 Bell Telephone computer sites. Monitoring equipment was operated at each site for at least 2.1 months; the average duration of monitoring at each site was 11.3 months. Their results are briefly summarized below.

1. 56% of the sites experienced at least one instance of the rms voltage (10 s average) outside the ANSI acceptable range from 106 to 127 V rms.
2. The temporary disturbances and their criteria had the following relative distribution:

   Sags 87.0% (less than 96 V rms, duration | 16 ms)
   Impulses 7.5% (more than 200 V peak)
   Outages 4.7%
   Surges 0.8% (more than 130 V rms, duration | 16 ms)
   TOTAL 100.0%

3. Half of the sags had durations of less than 0.12 s; 90% of the sags had a duration of less than 0.53 s.
4. Half of the outages had durations of less than 38 s; 90% of the outages had durations of less than 4.2 h.
5. The average duration of a surge was 0.10 s.

While there is some disagreement among the results of these studies, all of the studies found disturbances on the power line.

These disturbances must be removed for error-free operation of computers and other sensitive electronic equipments.

It is tempting to monitor power at each individual site to see if a power problem exists before money is spent on correcting power disturbances. However, experience shows that this is unnecessary. Power disturbances are likely to occur if one waits long enough, for example, one year of continuous monitoring. Such extensive monitoring is expensive and delays needed action. Monitoring for a short period of time (e.g., less than 2 weeks) is very unlikely to capture rare disturbances. For example, everyone has experienced a blackout that lasts more than an hour, yet continuous monitoring for several months at one site is unlikely to record such a blackout. Other disturbances are seasonal. Lightning is most likely during the summer. Monitoring during the winter is unlikely to find disturbances due to lightning.

It is important to recognize that monitoring that shows "no disturbances" does not prove that disturbances do not exist at a site. If the monitoring is properly done, such a result only shows that disturbances were not present during the monitoring. However, one can not justifiably conclude from such a result that disturbances will not occur during the future at that site.

Power line disturbances are erratic and unpredictable. Changes in equipment that is connected to the mains can change the rate of disturbances at a site. Since environment at a particular site changes, one cannot use past studies of disturbances at a site to predict the occurrence of future disturbances.

SOLUTIONS TO POWER DISTURBANCES

Many different kinds of devices are sold to remove disturbances from the power line. Some devices solve only one possible problem, while other devices may solve several problems. These devices will be discussed in the next several sections.

One of the most effective devices for removal of power disturbances is a line conditioner. Line conditioners (and their component parts: isolation transformers, AC voltage regulators, and low-pass filters) are the subject of Section 2. Section 2 also describes uninterruptible power supplies (UPS). These devices provide power from batteries during prolonged absence of the mains voltage.

Section 3 describes how to attenuate high-voltage pulses on the mains with metal-oxide varistors. A discussion of the use of a "dedicated line" is also included in Section 3.

Sections 4 through 7 describe the experiments that were performed on line conditioners and UPS units during this research project. The goals of this research project were (1) to determine how to test line conditioners and (2) to obtain general results about how to protect critical loads such as a desktop computer. These tests were limited to units sold for single-phase, 120 V rms, 60 Hz service with a maximum rated load between 400 VA and 550 VA.

Section 8 presents some simple practical advice, based on the information presented in Sections 2 through 7.

The results and conclusions in this report pertain only to line conditioners and UPS units for single-phase 120 V rms 60 Hz mains that are rated for loads of 500 VA. Products for larger or smaller loads may have different characteristics from the 500 VA units in this study. Equipment for three-phase service is also likely to have different characteristics.

SECTION 2

There are many electrical devices that are sold to remove disturbances from the power line. These can be grouped into several broad classes:

1. isolation transformers,
2. motor generator sets
3. voltage regulators,
4. line conditioners,
5. uninterruptible power supplies.

Isolation transformers are transformers with elaborate electrostatic shielding between the primary and secondary coils. The principal application of isolation transformers is to attentuate common-mode voltages (voltages that appear on both the hot and neutral conductors with respect to ground). They are often recommended for the removal of disturbances from the power line. An isolation transformer has no effect on differential-mode voltage fluctuations (e.g., sags, brownouts). Many isolation transformers contain a circuit that provides attentuation of high-frequency noise, although this is not required by the definition of an isolation transformer.

Voltage regulators provide an essentially constant rms voltage to the load for a wide range of input voltages and load currents. Voltage regulators are intended to remove "sags", "brownouts", and, possibly, moderate overvoltage conditions.

Line conditioners are comprehensive devices that combine the features of isolation transformers and voltage regulators and also provide attenuation of high-frequency noise. A typical line conditioner costs between about $400 and $500 for a unit that will operate a maximum load of 500 VA. Since the cost of a line conditioner is similar to that of the less versatile isolation transformer alone or that of the voltage regulator alone, it is cost-effective to use line conditioners as the basic element in the removal of power disturbances.

We will now consider isolation transformers and voltage regulators in detail. Then we will review techniques for attenuating high frequency noise on the mains. All three of these techniques (isolation, constant voltage, and high frequency noise attenuation) are components of line conditioners. This section concludes with a discussion of line conditioners and uninterruptible power supplies.

ISOLATION TRANSFORMERS

An isolation transformer is a transformer with elaborate electrostatic shielding between the primary and secondary coils, as shown in Fig. 2. This shielding reduces the capacitance between the primary and secondary coils to values of less than 1 pF. Some isolation transformers are advertised to have a coupling capacitance of less than 0.0005 pF. These small values of capacitance form a voltage divider with larger capacitance values that are shunted across the protected load, as shown in Fig. 3. The capacitance between the primary and secondary coils is shown by a dashed capacitor symbol, C1, in Fig. 3 to emphasize that C1 is a parasitic capacitance and not a component. The capacitance in shunt with the protected load is shown as C2 in Fig. 3. This voltage division produced by C1 and C2 attentuates common-mode voltages (voltages that appear on both the hot and neutral conductors with respect to ground). If C1 is 1 pF and C2 is 0.01 μF, we will obtain a common-mode voltage gain of 10^{-4}, which is an attenuation of 80 dB. Smaller gains (larger attenuations) can be obtained by making C1 smaller or C2 larger.

Many manufacturers of isolation transformers boast of fantastic attenuation by their products. For example, if C1 is 0.001 pF and C2 is 0.01 μF, we obtain 140-dB attenuation. A 6000-V transient on the line side of such an isolation transformer would be attenuated to 0.0006 V, a trivial value. This is impressive common-mode attenuation. An attenuation of 100 dB is probably the most that can be reasonably

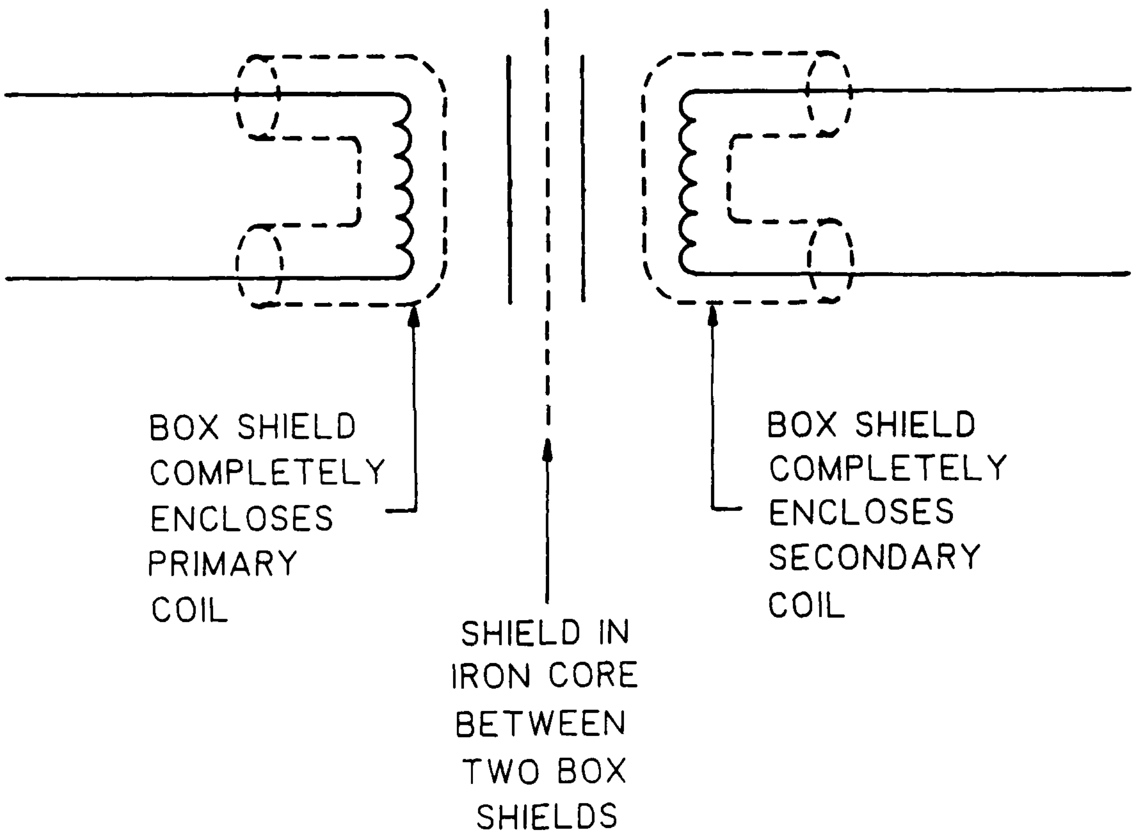
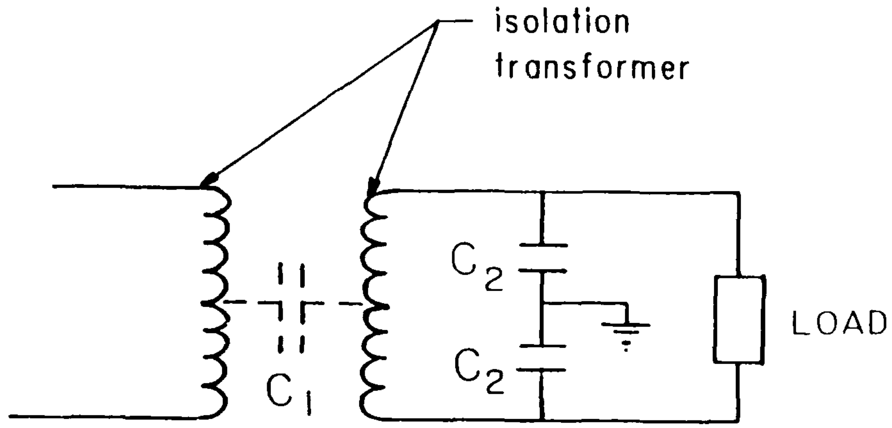


Figure 2. Isolation transformer construction.



$$C_1 < 1\,pF$$

$$C_2 \gtrsim 0.01\,\mu F$$

Figure 3. Isolation transformer.

required for protection of critical loads from common-mode transients and noise. It is doubtful whether there is any practical difference between attenuations of 100 dB and 140 dB (or more) when protection of loads is concerned. However, attenuation of more than 100 dB can be useful in carefully designed laboratory instrumentation systems to reduce coupling capacitance to ground through the power line.

Isolation transformers have no effect on low-frequency differential-mode phenomena such as sags, brownouts, surges, etc. In particular, Martzloff has shown that isolation transformers will not attenuate differential-mode high voltage transients (Ref. 10). Therefore an isolation transformer offers limited protection to critical loads. Most people who are tempted to purchase an isolation transformer should instead purchase a "line conditioner." The line conditioner, which is described later in this section, includes an isolation transformer and is more likely to solve vaguely specified electric power problems.

MOTOR-GENERATOR

We mention in passing that a motor-generator set with an insulating coupling between motor and generator provides complete isolation of loads from power line disturbances, except outages. The inertia of the flywheel can continue to supply power during interruptions of electrical power that have a duration of less than 0.1 s (e.g., flicker), which is an advantage compared to isolation transformers and line conditioners. However, variations in line voltage can cause variations in the frequency of the output waveform, which may be a disadvantage compared to isolation transformers and line conditioners. Motor-generator sets are not an economical way to provide power to critical electrical loads of less than about 1 kW.

VOLTAGE REGULATORS

There are four common techniques to provide AC voltage regulation in line conditioners: (1) the ferroresonant transformer circuit, (2) the tap-switching transformer, (3) electronic regulator circuits, and (4) the autotransformer. The first two techniques are more widely used, and our discussion will concentrate on them.

The operation of a ferroresonant transformer circuit is reviewed in References 11-15. The following description is grossly oversimplified but serves to convey the general idea. The ferroresonant transformer uses a core that is operated in "saturation," i.e., the magnitude of magnetic induction, B, is essentially independent of the magnitude of the magnetic field, H. Since the magnitudes of the input voltage, current in the primary coil, and the magnetic field, H, are all proportional, this makes the value of B essentially independent of the rms input voltage. If a resonant circuit were not present, the output voltage would be a crude square wave with the same frequency as the input voltage. An inductor-capacitor resonant circuit converts the output voltage to a quasi-sinusoidal waveform. If a sinusoidal output waveform is desired, a "harmonic-neutralized" design should be specified (Ref. 16). This will typically provide less than 3% harmonic distortion.

A schematic diagram of a ferroresonant transformer is shown in Fig. 4.

The ferroresonant circuit has several outstanding advantages compared to other types of regulators:

1. Excellent voltage regulation: output voltage is typically 120 ± 3 V for input voltages between 95 and 138 V (no load to full rated load conditions).

2. The ferroresonant transformer is inherently short-circuit proof. If the output terminals are shorted, the magnitude of the output current will be about 1.5 to 2.0 times the maximum rated load current. Under these conditions the transformer will act as a current source. This will <u>not</u> harm the transformer.

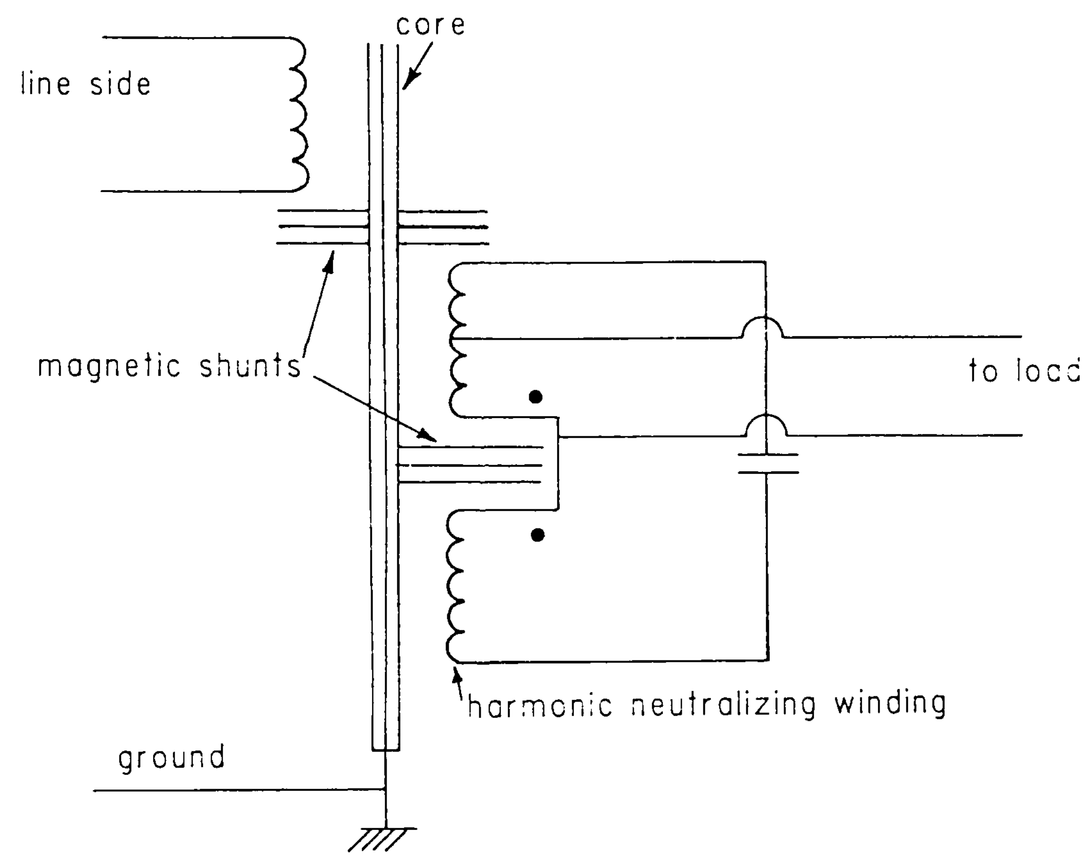


Figure 4. Ferroresonant transformer.

3. The ferroresonant circuit tends to ignore brief losses of input power. There is essentially no change in rms output voltage when the input voltage is zero for durations of 2 to 4 ms, since the resonant circuit continues to oscillate for several cycles without additional energy input.

4. High reliability. The only components in a ferroresonant transformer are one transformer (with multiple windings) and one capacitor. There are no moving parts and no semiconductors.

5. The output waveform of the ferroresonant transformer is essentially independent of the input waveform. When one is concerned with harmonic distortion, one should be sure to specify a "harmonic-neutralized" ferroresonant transformer.

However, the ferroresonant transformer has several major disadvantages:

1. Because the transformer core is driven into saturation, the transformer can be inefficient. If the ferroresonant transformer is operated at half its maximum rated load, the typical efficiency is only about 65% due to large losses in the core. (If the unit is operated with its rated load and with an input voltage that is approximately the same as the output voltage, typical efficiencies are between 80% and 95%. These figures are often cited by vendors as evidence of "good efficiency.") The ferroresonant transformer core operates at 45 to 85 celsius above ambient temperature due to power dissipated in the core. This heat burden can be a serious consideration in computer rooms that need cooling.

2. The ferroresonant transformer is massive. A 500 VA ferroresonant unit has a mass of about 20 kg, about 75% more

than for a tap-switching line conditioner of the same VA rating.

3. Because a resonant circuit with a fixed resonance frequency is used, the device is sensitive to changes in frequency of the input waveform. For a typical ferroresonant transformer, if the input frequency deviates from the design frequency, the output voltage will change by about 1.5% to 2% for each 1% change in input frequency. This effect is inherent in the performance of a resonant circuit that is not driven at the resonance frequency. This is not a serious problem when the input power is obtained from public utilities. However, when the input power is obtained from local generators that are driven by an internal combustion engine, the error in input frequency is often several percent.

4. An air gap is sometimes included in ferroresonant transformers (Ref. 17). Magnetic fields from this air gap can disturb the cathode ray tube (CRT) display of computer terminals. We have observed this effect even with a distance of several meters between the ferroresonant transformer and CRT. Some models of ferroresonant transformers do not disturb CRT displays.

5. Ferroresonant transformers produce audible noise.

A second type of AC voltage regulator is the tap-switching transformer. A schematic drawing is shown in Fig. 5. A standard two coil (primary and secondary) transformer is provided with multiple terminals (called "taps") on either coil to compensate for variations in the magnitude of the input (primary) voltage. Depending on the number of taps, one can obtain arbitrarily good regulation. A common specification is for the output voltage to remain constant within ±5% for an input voltage change of ±12%. While this regulation is not as good as that of a ferroresonant circuit, it is still acceptable for

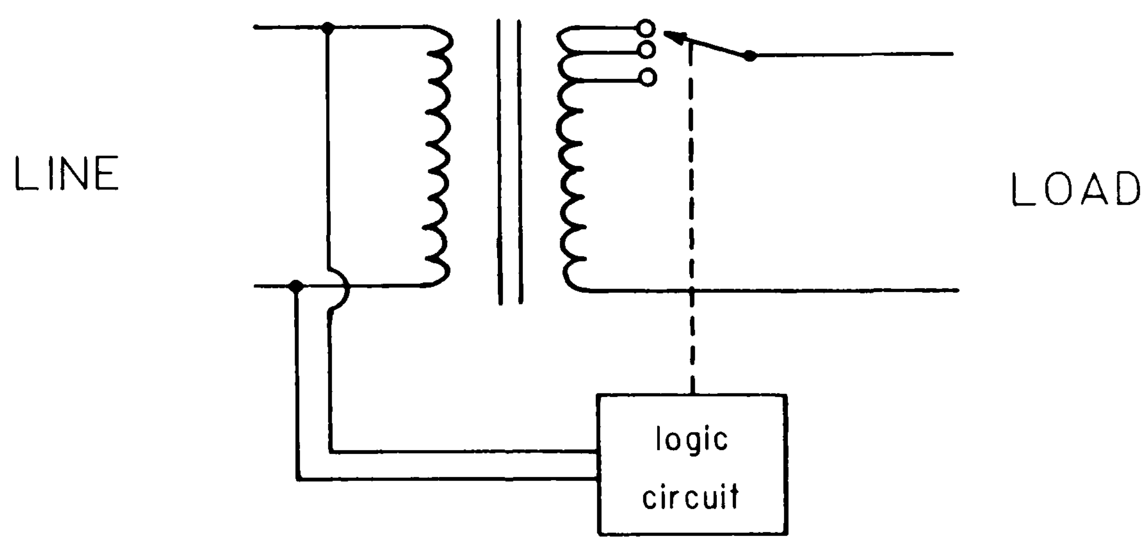


Figure 5. Tap-switching transformer.

most critical applications (e.g., computers, electronic instruments). The tap switching is usually done with a triac, which is faster, more reliable, and less noisy than a power relay.

A third type of AC voltage regulator is the electronic circuit shown in Fig. 6 and discussed in Reference 18. Internal circuits convert the mains voltage to a constant voltage (DC). The regulated DC power is then converted back to AC by an oscillator. An amplifier and output transformer drives the load. This electronic regulator removes all power disturbances except blackouts. Protection against blackouts can be obtained simply by placing a battery bank across the energy storage capacitor in the DC power supply. When batteries are added to the electronic voltage regulator, a true "uninterruptible power supply," is obtained, a device that is described later in this section.

Electronic voltage regulators are much more expensive than the other three types of AC voltage regulators. If one is going to spend the money for an electronic AC regulator, one may as well pay the relatively small additional cost of a true uninterruptible power supply. Electronic voltage regulators are the only common device that will correct for deviations in the frequency of the mains. However, as mentioned in Section 1, such frequency variations are rarely a problem with power from a commercial utility.

The autotransformer is a fourth type of AC voltage regulator. The autotransformer (also known as a "variable ratio transformer" or by the trade name "Variac") provides no isolation, since the primary and secondary share turns on the same coil. An electronic circuit that senses the rms voltage can be used to drive a servo motor to maintain an approximately constant rms output voltage. Because of inertia of moving parts, a motor-driven autotransformer cannot respond quickly to changes in line voltage. Therefore, the autotransformer is useful mainly to correct for variations in rms line voltage that persist for more than one second. The autotransformer fails to meet

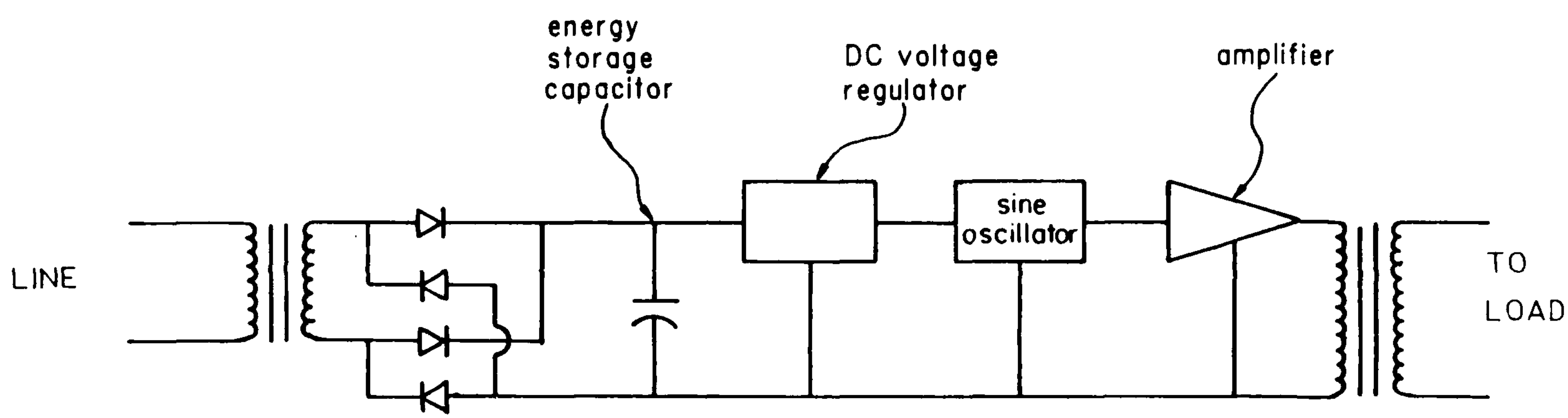


Figure 6. Electronic AC voltage regulator.

our requirements for a line conditioner and will not be considered further.

HIGH-FREQUENCY NOISE ATTENUATION

High-frequency noise can be a problem for sensitive electronic equipment such as computers and electronic instrumentation. Such noise can come from radio or radar transmitters that illuminate the power line. Some electronic equipment can be a source of high-frequency noise.

High-frequency noise on the mains can be attenuated with a low-pass filter that contains series inductors and shunt capacitors, as shown in Fig. 7. The manufacturers of most computers and electronic instruments install such a filter where the mains cord enters the chassis.

The simple circuit that is shown in Fig. 7a attenuates only common-mode noise. The inductor, which has two coils, is wound on a ferrite toroid. The inductor is connected so that the voltage drop across one coil opposes the voltage drop across the other coil. This has two advantages: the inductor does not affect the differential-mode voltage across the load and the differential-mode current does not saturate the ferrite core. This circuit can be designed to provide attenuation between 20 dB and 50 dB for common-mode signals between about 0.5 MHz and 30 MHz.

The more complicated circuit shown in Fig. 7b combines both common-mode and differential-mode attenuation circuits.

A better way to attenuate high-frequency noise is to include some inductance in series with the transformer primary. If a relatively large series inductor is inserted in the primary side, the voltage across both primary and secondary coils of the transformer will be reduced. Compensation for this effect can be obtained by increasing the number of turns in the secondary coil. The large series

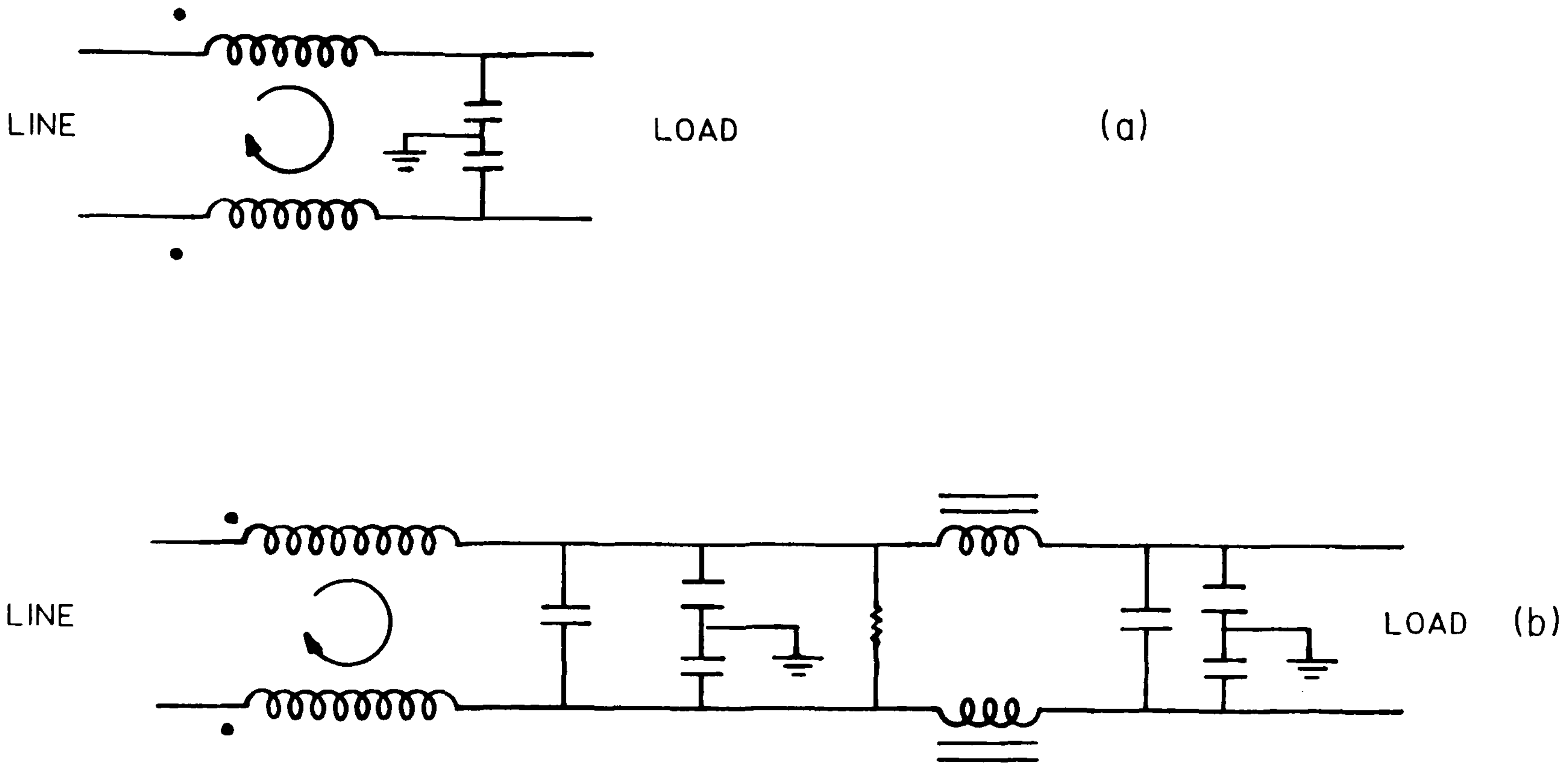


Figure 7. RFI filter modules.

inductance in series with the primary coil gives much better rejection of noise at frequencies below 0.5 MHz than common inductor-capacitor filter modules.

LINE CONDITIONER

An AC line conditioner is a device that accomplishes all of the following three items:

1. Provide voltage regulation. When the rms input voltage is between 95 and 130 V rms, the output voltage should be between 110 and 125 V rms for any load condition between no load and full load.

2. Provides at least 50 dB differential-mode attenutation at frequencies above 100 kHz.

3. Provide isolation: no more than 1 pF capacitance between the input and output terminals. This, when combined with capacitance shunted across the load, attenuates common-mode transients and noise.

INSTALLATION OF LINE CONDITIONERS

We mention that all of the units in a system must be connected to a line conditioner, in order that the system be protected from disturbances on the mains. This simple rule is often violated in computer systems where the computer is connected to the mains through a line conditioner, but the peripherals, such as the printer or terminals, are not. Since the peripherals are connected to the computer via interfaces, transient overvoltages or noise could propagate from the mains through the peripherals to the computer. The simplest solution is to have one large line conditioner that serves the entire computer system, provided that all of the components are located near each other.

When the line conditioner is installed, the input power cord and group of output power cords must be physically separated as much as possible. This is most easily accomplished when the input and output connectors are on opposite sides of the line conditioner. Because one of the functions of a line conditioner is to provide isolation, there should be no more than 1 pF between input and output circuits. If the input and output power cords are routed near each other, the parasitic capacitance between input and output cables will vitiate the isolation provided by the line conditioner. In addition to parasitic capacitance, there may be significant mutual inductance between the input and output cords that are near each other. One of the worst things to do is to bunch the input and output cords together and secure them with a tight plastic cable tie.

UPS

Temporary loss of mains power can be avoided by using an uninterruptible power supply (UPS) at the critical load. A UPS supplies power from rechargeable batteries during an outage or blackout. UPSs tend to be expensive. A unit that has a sinusoidal output voltage at 120 V rms and can supply 400 VA for 20 to 30 minutes costs between about $800 and $2000 in 1985. Since the time for battery operation is limited, an orderly shutdown of the computer system should be begun if the mains power is not restored within a few tens of seconds after the outage begins. If operation is required during prolonged power interruptions (e.g., medical life-support systems, security systems, critical communication systems, or military systems), then an internal combustion engine-generator set is required. A battery operated UPS can supply power until the engine is started.

There are two basic kinds of UPS units, illustrated in Fig. 8, which are called a "true UPS" and a "standby UPS".

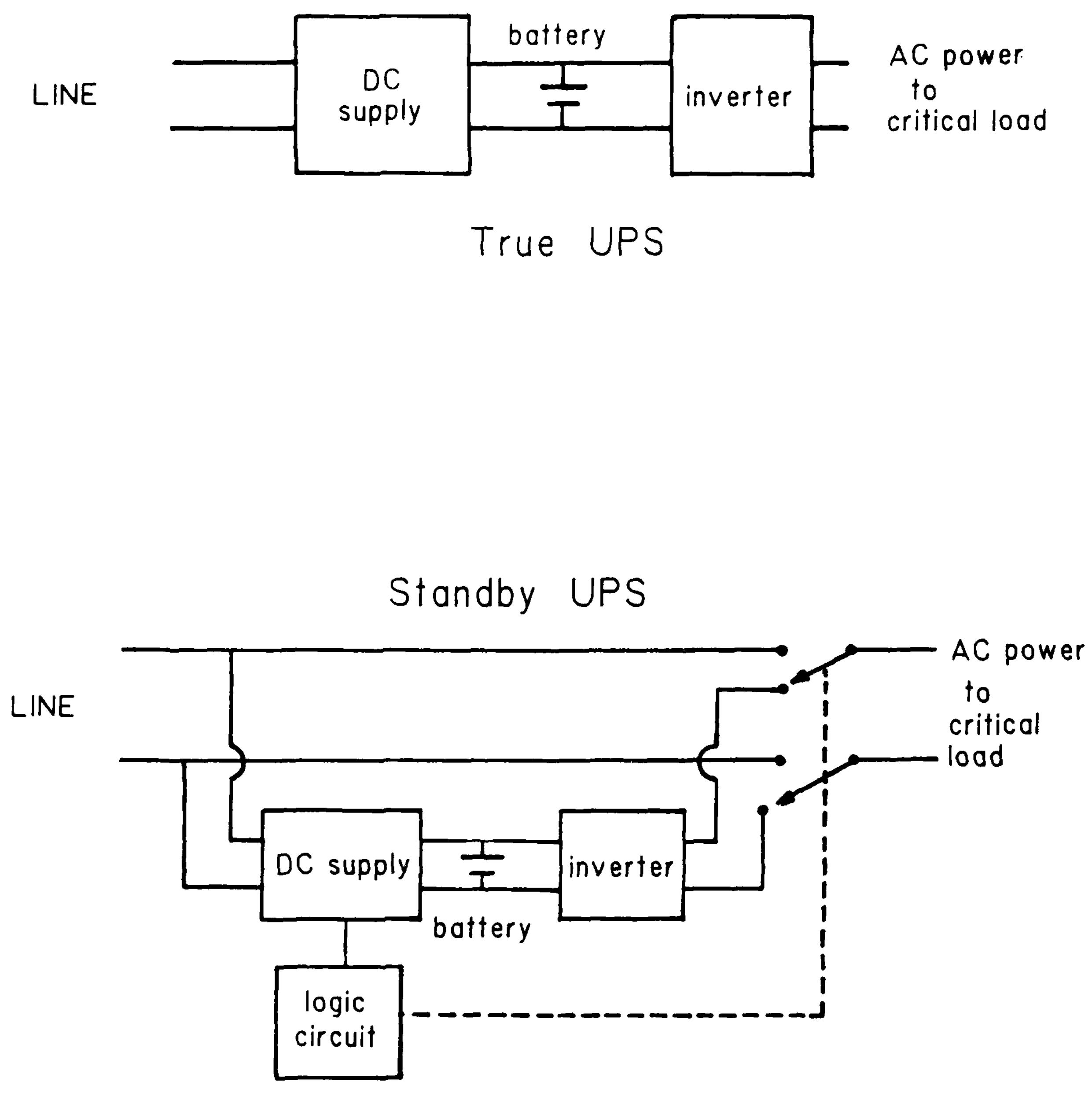


Figure 8. Schematics of two types of UPSs.

TRUE UPS

The true UPS is always connected between the mains and critical load. Therefore, it eliminates the effects of voltage reductions, high-voltage pulses, outages, high-frequency noise, harmonic distortion, and frequency variations at the critical load. However, since the DC supply in the true UPS must both charge the batteries and operate the inverter after the mains power is restored following an outage, the DC supply must be larger and more expensive than in the standby UPS. Some manufacturers avoid this problem by having a separate battery charger circuit in their true UPS. Regardless of the circuit details, true UPSs tend to be more expensive than a standby UPS. A typical true UPS has a bypass switch that connects the mains directly to the critical load if the UPS should fail.

STANDBY UPS

The other kind of UPS, called a "standby UPS", normally connects the mains directly to the critical load. When the mains voltage decreases to less than about 105 V rms (either due to a voltage reduction or an outage), a logic circuit switches a relay and connects the critical load to the output of the inverter. Power to the critical load is interrupted for about 0.01 s while the relay changes state. This brief interruption is unlikely to cause any problem. However, the brief interruption is responsible for the distinction between the "true" and "standby" UPS.

Manufacturers' literature for a "true" UPS often disparages the "standby" UPS because it briefly interrupts the power. However, it is important to realize that most electronic loads contain a DC power supply that operates the electronic circuit. The line current to these power supplies is composed of pulse that typically repeat every half cycle (8 ms on 60-Hz system). An interruption of about 10 ms when a standby UPS switches is equivalent to loss of less than one cycle of the AC power at 60 Hz. Most power supplies should be able to tolerate this without affecting the DC output voltage.

In a conventional linear DC power supply, a full-wave rectifier circuit is used to convert the sinusoidal mains voltage to a pulsating unipolar voltage. A filter capacitor (which often has a value of many thousands of microfarads) converts the pulsating voltage from the rectifier to an approximately constant voltage. Because the filter capacitor is present, the rectifiers conduct for only a small fraction of each period of the mains voltage. This is an important point. When the relay in the standby UPS changes state, the rectifiers in the linear power supply remain nonconductive for one or two extra half periods of the mains voltage. The voltage across the filter capacitor will decrease monotonically during this time but will not have an adverse effect on the operation of the load provided that the filter capacitor has adequate capacity. The sag in voltage across the filter capacitor should be absorbed in the electronic voltage regulator circuit and should not appear at the output of the DC supply.

Similarly, filter capacitors in switching power supplies should also provide continuous output voltage during interruptions of the mains for less than one cycle.

Users should be aware that inexpensive UPS units often have a rectangular output waveform instead of a sinusoidal waveform. A rectangular output waveform may be acceptable to a switching power supply but may cause problems with linear power supplies and motors.

We recommend the combination of a line conditioner and a standby UPS for small systems (less than 800 W). Such a combination is less expensive and probably more reliable than a true UPS. We discuss this issue further in Sections 4, 6, and 8.

SECTION 3

The two previous sections reviewed the available knowledge about line conditioners and uninterruptible power supplies, the major subject of this report. However, in the broader context of solving problems with electrical power for critical loads, we need to mention two other techniques: The first is the use of varistors to attenuate transient overvoltages; the second is the use of a dedicated branch to avoid power problems.

Because this report is concerned with the performance and application of line conditioners, varistors are discussed only in the context of being combined with a line conditioner near a critical load. Additional varistors should be connected at the point of entry to protect against lightning and EMP threats. Varistors that are designed for connection at the point of entry are commercially available.

USING MOVs AT THE MAINS FOR TRANSIENT OVERVOLTAGE PROTECTION

Substantial protection from transient overvoltages can be obtained by installing three metal oxide varistors as shown in Fig. 9. This group of varistors should be installed at the primary of the transformer in the line conditioner or upstream from the line conditioner.

Specifications for appropriate metal oxide varistors will be discussed later in this section.

Varistor V1 protects against differential-mode (also called normal-mode) transient overvoltages. Varistors V2 and V3 together protect against common-mode transient overvoltages. Varistors V1 and V2 are both exposed to the mains voltage during normal operation. These two varistors must <u>not</u> conduct at voltages whose magnitude is less than about 180 V, the peak value for 130 V rms sinusoidal waveform.

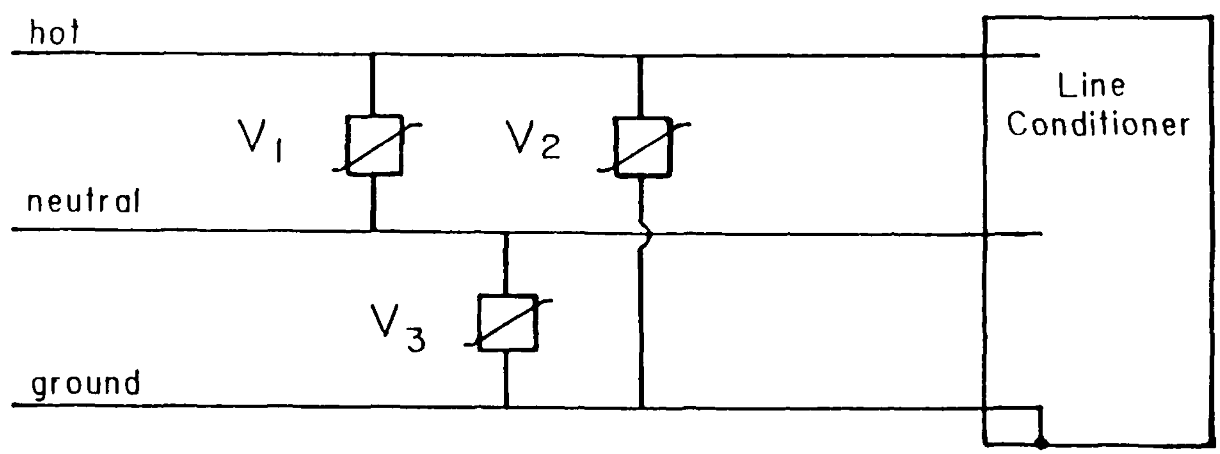


Figure 9. Connection of MOVs to mains.

Varistors should not be used for steady-state voltage regulation. When a varistor conducts, its temperature increases due to the power dissipated in it. The conduction voltage for metal-oxide varistors decreases as the varistor temperature increases, so thermal runaway will occur if the varistor conducts appreciable steady-state current during normal operation.

Varistor V3 has no more than a few volts across it during normal operation. However, V3 should also be specified to not conduct when a magnitude of less than 180 V is across it. There are several reasons for this specification:

1. There is no *a priori* reason to expect V3 to be subjected to less energetic transients than V2. Therefore, V3 and V2 should have the same rating for maximum energy that can be absorbed in a pulse and peak pulse current. For varistors of a given cross-sectional area, devices with a smaller conduction voltage have a smaller peak current and maximum energy rating.
2. If V3 and V2 have appreciably different conduction voltages, common-mode transient overvoltages will be converted to differential-mode overvoltages. Common-mode voltages are easily attenuated by isolation transformers, line conditioners, or low-pass filters. It is more difficult to attenuate differential-mode voltages, particularly for transients with durations of tens of microseconds or more. This consideration does not require matched devices for V3 and V2, but their nominal conduction voltages should be similar.
3. There is also the possibility that the hot and neutral conductor may be reversed by a wiring error. This error would cause V3 to see the mains voltage.

USING MOVs AT THE LOAD FOR TRANSIENT OVERVOLTAGE PROTECTION

An additional group of three varistors should be installed near each protected load, as shown in Fig. 10. This group of varistors near the loads attenuate transients that are generated inside the chassis of one protected load and propagate toward other protected loads. This group of varistors also provides additional attenuation of transients that propagate from the mains toward the protected loads.

Specifications for appropriate MOVs will be discussed later in this section.

An ideal arrangement is to have one group of varistors inside the chassis of each load. Not all manufacturers provide such protection for their equipment, and space may not be available for installation of varistors by the user as a retro-fit. A convenient compromise is to install a group of three varistors inside an outlet strip and connect all protected loads to an outlet strip that contains such protection.

SPECIFICATIONS FOR VARISTORS AT MAINS

It is important to use varistors that have an adequate capacity to absorb transient overvoltages to which they will be exposed. We offer the following general specifications for varistors that are connected to a single-phase branch of a nominal 120 V rms service with a 20 A (or less) circuit breaker:

1. $185 < V_N < 300$ V
   V_N is the varistor voltage at 1 mA DC current,

2. less than 420 V across the varistor during a 8x20 μs test current with a 100 A peak value; less than 800 V across the varistor during a 8x20 μs test current with a 5 kA peak,

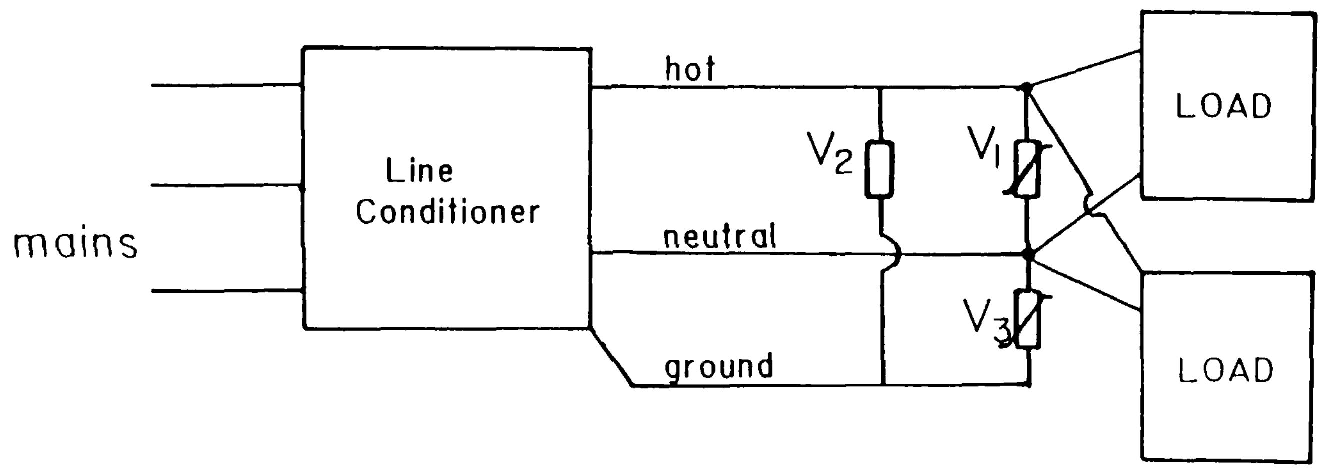


Figure 10. Connection of MOVs at load.

3. will survive a 6 kA peak current (8x20 μs waveshape) without rupturing the case or loss of protective function,

4. able to tolerate an at least a million pulses of 60 A peak current (8 x 20 μs waveshape) without changing V_N by more than ±10%.

With ZnO varistor technology available in 1985, such a varistor will have a diameter of 20 mm or more.

If larger steady-state voltages than 120 V rms are expected, the specification for a minimum conducting voltage, V_N, should be increased to more than 185 V.

SPECIFICATIONS FOR VARISTORS AT LOAD

We offer the following general specifications for varistors that are connected downstream from a line conditioner. Two cases are considered, one "moderate duty" and one "light duty". In both cases single-phase service with a nominal level of 120 V rms is assumed.

A moderate duty application satisfies the following requirements:

1. Protected loads are connected to 120 V rms mains (170 V peak),
2. Total power consumed by all protected load(s) is less than 1500 W,
3. The loads do not contain a potent source of transients,
4. There are additional varistors upstream.

Typical "moderate duty" applications include varistors inside an outlet strip to protect several loads. Under these moderate duty conditions, an appropriate metal oxide varistor might have the following specifications:

1. $185 < V_N < 230$ V
   V_N is the varistor voltage at 1 mA DC current,

2. less than 350 V across the varistor during a 8x20 μs test current with a 100 A peak value,

3. will survive a 6 kA peak current (8x20 μs waveshape) without rupturing case or loss of protective function,

4. able to tolerate an at least a million pulses of 60 A peak current (8x20 μs waveshape) without changing V_N by more than ±10%.

With ZnO varistor technology available in 1985, such a varistor will have a diameter of at least 20 mm.

A "light-duty" application is one which satisfies the following three criteria:

1. Protected loads are connected to 120 V rms mains (170 V peak),
2. Total power consumed by protected load is less than 500 W,
3. The loads do not contain a potent source of transients,
4. There are additional varistors upstream.

A typical light duty application would include varistors that are mounted inside a chassis. Under these light-duty conditions, an appropriate metal oxide varistor might have the following specifications:

1. $185 < V_N < 230$ V
   V_N is the varistor voltage at 1 mA DC current,

2. less than 350 V across the varistor during a 8 x 20 μs test current with a 50 A peak value,

3. will survive a 4 kA peak current (8x20 μs waveshape) without rupturing case or loss of protective function,

4. able to tolerate an at least a million pulses of 50 A peak current (8x20 μs waveshape) without changing V_N by more than ±10%.

With ZnO varistor technology available in 1985, such a varistor will have a diameter of 14 mm or more.

DEDICATED LINE

A "dedicated line" is a branch provided by an electrician so that no other devices or outlets are connected to the same branch that serves a critical load. A dedicated line is desirable since faults caused by other equipment in the building will not interrupt power to the critical load by tripping the circuit breaker. A dedicated line also avoids voltage reductions caused by currents in other loads and the resistance of the wire inside the building. For example, consider the situation shown in Fig. 11. Current drawn by the arc welder produces a voltage drop along the wire that connects it to the circuit breaker panel. This voltage drop does not appear at the computer, which is on a separate branch. In contrast, current drawn by the lamps and coffee pot in Fig. 11 does decrease the voltage at the typewriter.

One might also expect a dedicated line to offer less high-frequency noise that originates at sources inside the building with the critical load.

However, the dedicated line is usually connected at the circuit breaker panel to the same distribution transformer that supplies other loads, which compromises the dedicated line. For example, if the arc welder in Fig. 11 draws a large current, the line voltage will be reduced at the computer, owing to the resistance of the wires outside

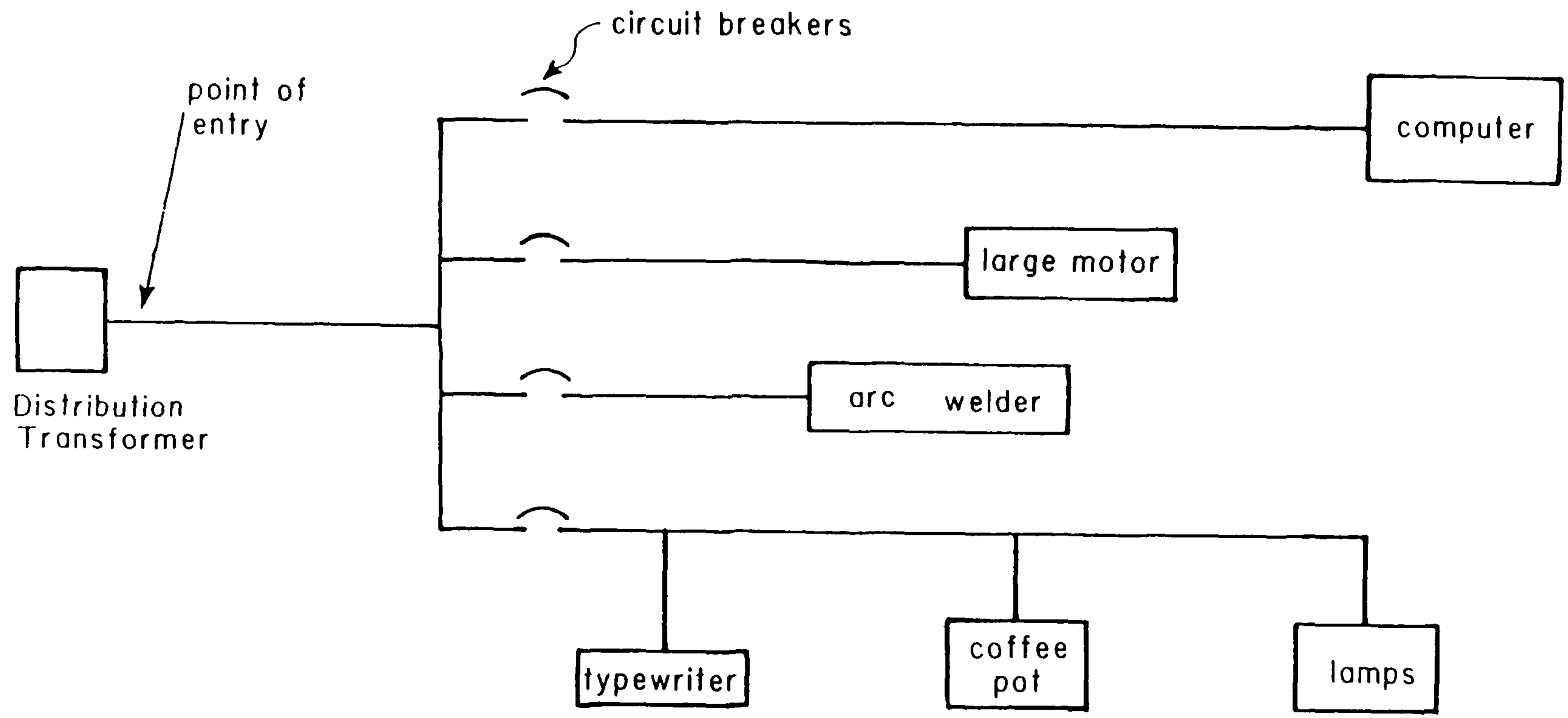


Figure 11. Use of dedicated line for computer.

of the building and the output impedance of the distribution transformer.

A dedicated line offers no protection from voltage reductions or outages that originate outside the building. High-voltage transients will still adversely affect the load on a dedicated line. While a dedicated line is desirable, it alone does not offer adequate protection for critical systems.

SECTION 4

INTRODUCTION TO TESTS

The goals of this research project were (1) to determine how to test line conditioners and (2) to obtain general results about how to protect critical loads such as a personal computer. All of the units that we tested were rated by their manufacturer for service on single-phase 120 V rms mains with a frequency of 60 Hz and a maximum load of about 500 VA. The models tested are listed in Table 1. The cost data are for single quantities in April 1985 and do not include shipping charges.

TABLE 1. PRODUCTS TESTED

Manufacturer	Model	Type	Cost
Line Conditioners Tested			
Sola	63-13-150	500 VA ferroresonant	$ 397
Topaz	70301 "Line 2"	500 VA tap-switcher	$ 446
Deltec	GSC560A	500 VA tap-switcher	$ 495
Oneac	CM1105 "Micromate"	550 VA filter	$ 404
UPSs Tested			
Topaz	84462 "Powermaker"	400 VA standby UPS	$ 805
Deltec	GSU3056 "Micro UPS"	500 VA true UPS	$1100

We had planned to test the Deltec model GPC560 ferroresonant line conditioner, but Deltec discontinued production of ferroresonant devices prior to our order. Topaz introduced a ferroresonant line conditioner in 1986 after most of our experiments were completed.

The Oneac device is advertised as a "power conditioner." It does not provide any line or load regulation, nor does it provide isolation.

Therefore the Oneac does not meet the definition of a line conditioner that is presented in Section 2 of this report. The Oneac device was not subjected to the dynamic line and load regulation tests that are reported in Sections 5 and 6. However, we did subject the Oneac device to the same high voltage transient tests as were used to test the line conditioners.

STEADY-STATE REGULATION TEST METHODS

Steady-state line regulation tests were performed on several line conditioners and UPS units. The schematic drawing for the tests is shown in Fig. 12. The variable input voltage is provided by an autotransformer that is rated to supply 10 A rms at 0 to 140 V rms. This autotransformer was operated at less than half of its maximum output current in order to reduce effects of loading on output voltage.

Two voltmeters (Keithley Model 179A) were used to measure input and output voltage. These meters are designed to measure the true root mean square (rms) value of the voltage. We always used them on the 200 V rms scale. The manufacturer's specifications are for an accuracy of ±1 V rms when 120 V rms is indicated on this scale, for frequencies between 45 Hz and 10 kHz. The resolution is 0.01 V rms. The voltmeters were interfaced to a computer via an IEEE-488 bus. The computer interface allowed large quantities of data to be taken quickly without transcription errors.

Measurements were begun with the input voltage of about 138 V rms. The input and output voltage were then read and stored by the computer. The input voltage was then decreased by 1 to 2 V rms. The system was allowed to settle for a few seconds. The input and output voltages were then read and stored by the computer. This process was repeated until the input voltage of about 80 V rms was reached. For tests with resistive loads, we continued to decrease the input voltage below 80 V rms, with typical increments of 2 to 3 V rms. However, we

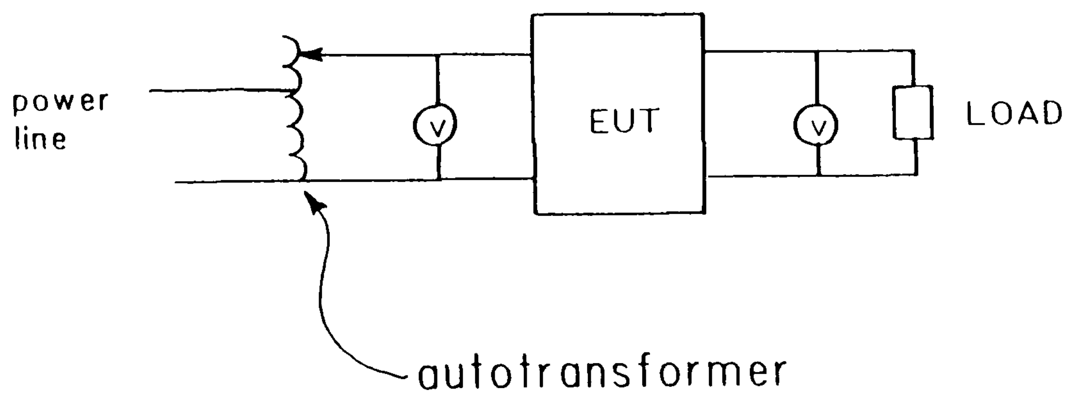


Figure 12. Steady state regulation tests.

were careful to determine the input voltage at which the ferroresonant line conditioner ceased to regulate to within about ±0.5 V rms.

STEADY-STATE LINE REGULATION RESULTS

The steady-state input vs. output voltages for the Sola ferroresonant, Topaz tap-switching, and Oneac device are shown in Fig. 13 for a 35 Ω load. For simplicity the results for the Deltec tap-switching line conditioner are not shown in Fig. 13. The performance of the Deltec conditioner was similar to that of the Topaz tap-switching line conditioner. The 35 Ω load represents about 80% of the full rated load of the line conditioners. Two dashed lines are drawn across Fig. 13 to indicate an output of 110 and 125 volts rms. These two levels were arbitrarily assigned to represent acceptable rms voltage values for sensitive electronic equipment.

The Oneac device does not provide any voltage regulation. The inclusion of data from tests of the Oneac device in Fig. 13 is a convenient representation of a direct connection between input and output terminals for the steady-state conditions of this test.

At input voltages greater than 125 V rms the Topaz acted as a step-down transformer. Between 111 and 125 V rms the Topaz tap-switching line conditioner's performance paralleled that of the Oneac device. In this range the Topaz line conditioner behaved as a 1:1 transformer. At input voltages less than 111 V rms the Topaz acted as a step-up transformer. Input voltages between 99 and 111 V rms corresponded to one step-up tap. When the input voltage decreased below 99 V rms, the output of the Topaz line conditioner was connected to a second step-up tap, which provided additional voltage gain. When the input voltage declined to 86 V rms, the output voltage of the Topaz was 110 V rms, the arbitrary minimum acceptable value.

Both the Deltec and Topaz tap-switching line conditioners have 4 taps. The discontinuities in output voltage caused by switching a tap were between 10 and 14 V rms.

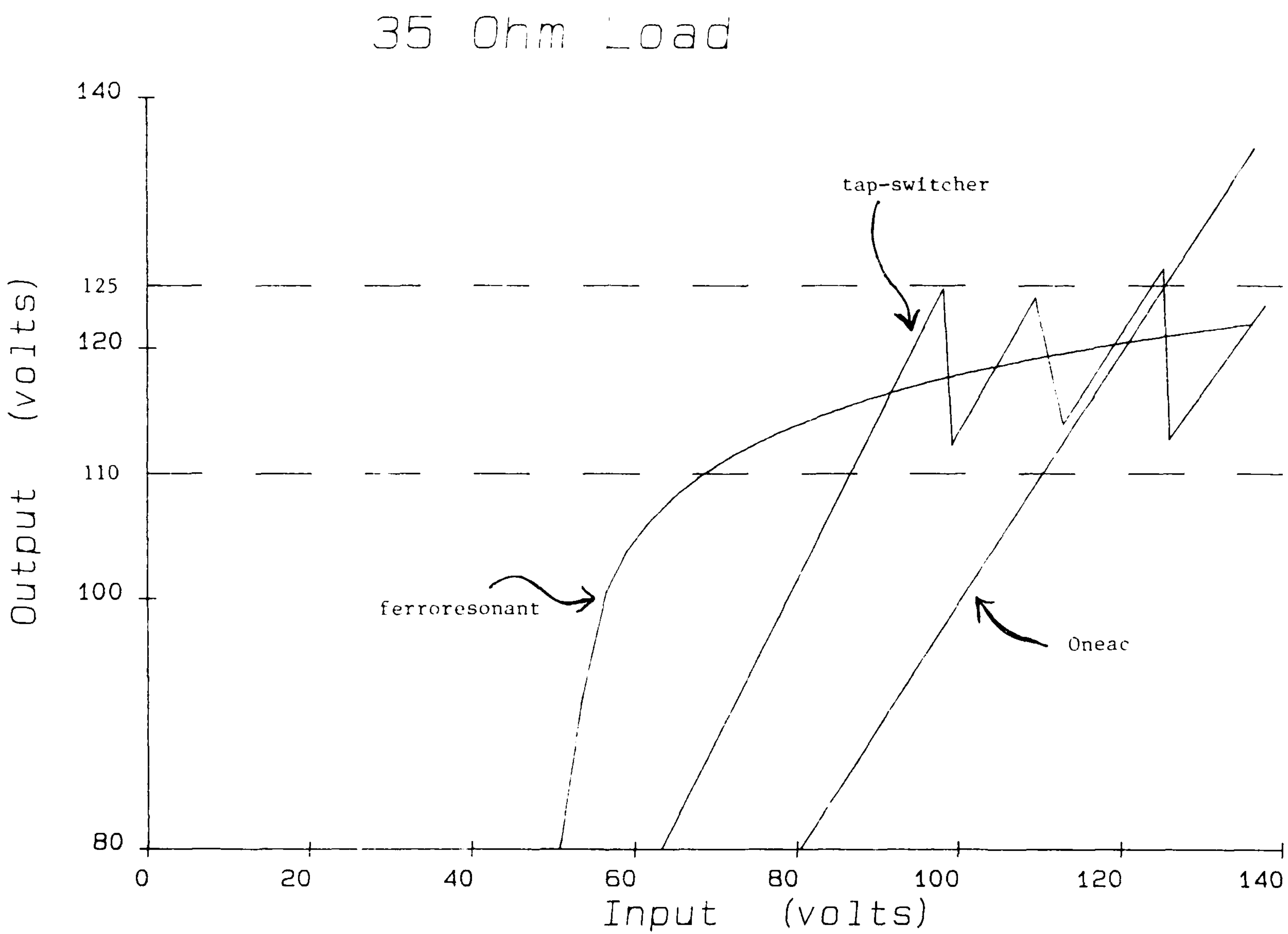


Figure 13. Rms output voltage as function of input voltage for three different devices with 35 Ω load.

The output voltage of the ferroresonant line conditioner varied smoothly over the range of the input voltage, unlike the tap-switching regulators that had discontinuities in the output voltage.

When the input voltage decreased to 69 V rms, the output voltage of the Sola ferroresonant line conditioner with a 35 Ω load was 110 V rms, the arbitrary minimum acceptable value.

The tests were repeated with a 150 Ω load, which is about 20% of the maximum rated load of these line conditioners. The results are shown in Fig. 14. The results of these tests are qualitatively similar to those with the 35 Ω load, shown previously.

When the input voltage declined to 83 V rms, the output voltage of the Topaz tap-switching line conditioner was 110 V rms, the arbitrary minimum acceptable value. The Sola ferroresonant line conditioner with a 150 Ω load maintained an output of at least 110 V rms for an input greater than 31 V rms. Clearly the ferroresonant technology is better than common tap-switching regulators when reductions in mains voltage below about 80 V rms are expected.

The ferroresonant line conditioner also provided better voltage regulation during these steady-state tests than the tap-switching line conditioners did. We do not believe that the discontinuities in the tap-switching output voltage would cause a problem with most computer systems. However, users of equipment that is sensitive to mains voltage may appreciate the better steady-state voltage regulation of the ferroresonant line conditioner.

The steady-state voltage regulation was measured with a 15 μF capacitative load. The results were similar to those for a 150 Ω resistive load, with one exception. The output voltage of the Deltec tap-switching linc conditioner was less than 30 V rms for any input voltage between 0 and 140 V rms. Due to the inability of the Deltec tap-switching line conditioner to operate a capacitative load, we did

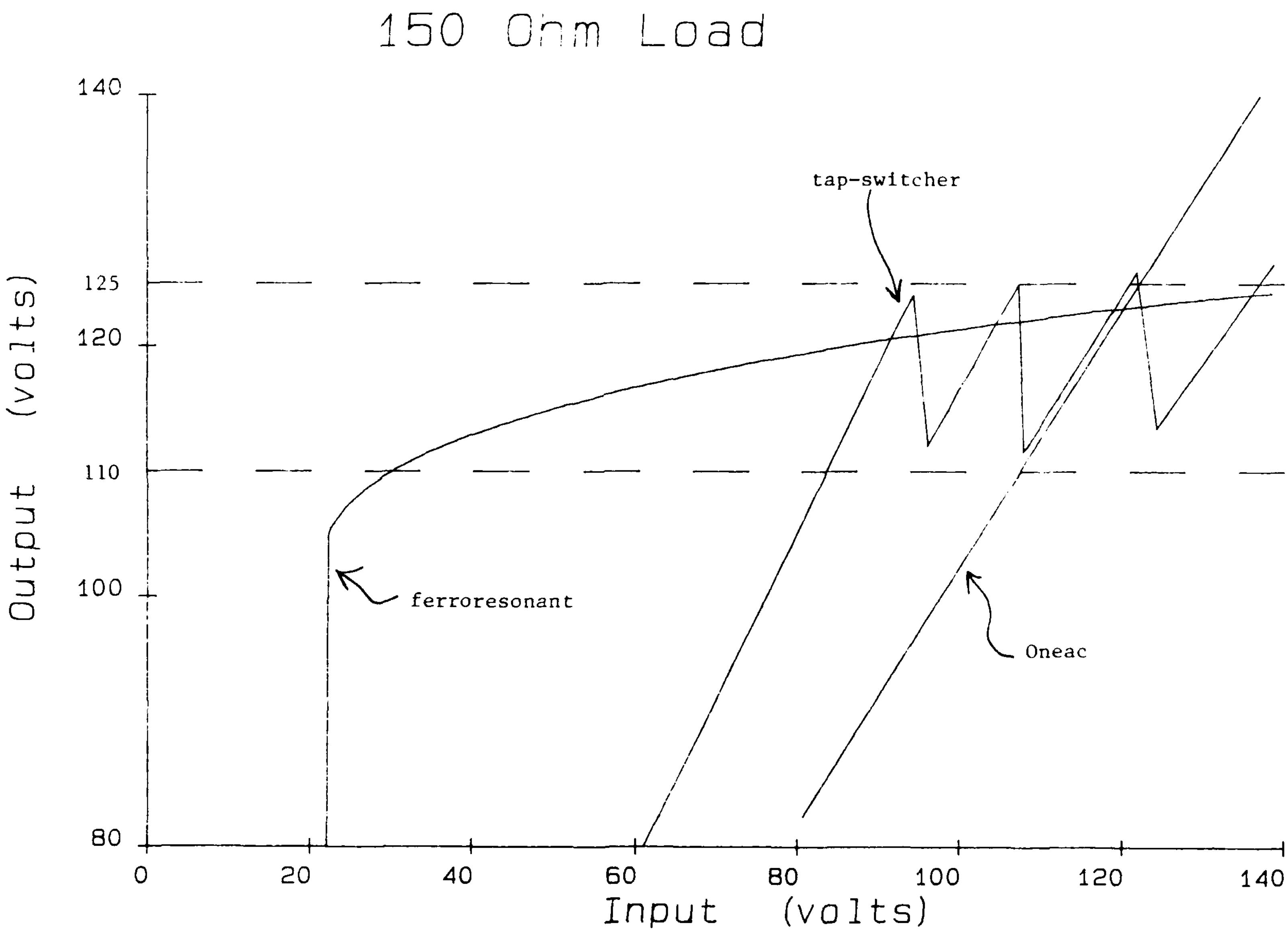


Figure 14. Rms output voltage as function of input voltage for three different devices with 150 Ω load.

not perform additional regulation tests on it. It was, however, included in the high voltage pulse tests.

The steady-state voltage regulation was also measured with a 1/12 hp motor as a load. The results were similar to those for resistive loads.

STEADY-STATE LOAD REGULATION RESULTS

The incremental output resistance of the line conditioner is a useful parameter to characterize the response of the conditioner to a change in load resistance or current. Conditioners with a smaller value of output resistance will have a smaller change in rms output voltage, a desirable feature, when the rms output current changes. We used Equation 1 to calculate the value of the incremental output resistance, r_{out}.

$$r_{out} = (V_1 - V_2) / \left(\frac{V_2}{R_2} - \frac{V_1}{R_1} \right) \quad (1)$$

where R_1 = 35 Ω

R_2 = 150 Ω

V_1 is the rms output voltage when load was R_1. V_2 is the rms output voltage when the load was R_2. The denominator of Equation 1 is the change of rms output current for the line conditioner. The input voltage was held constant at 120 V rms for all units except the Deltec tap-switching line conditioner. Because the Deltec tap-switching conditioner changed taps near 120 V rms, it was tested with an input voltage of 123 V rms. In this way the same tap was used for loads R_1 and R_2 for the tap-switching line conditioner. The computed value of the output resistance is given in Table 2.

TABLE 2. INCREMENTAL OUTPUT RESISTANCE

Sola ferroresonant	1.0 Ω
Topaz tap-switcher	1.1 Ω
Deltec tap-switcher	1.8 Ω
Oneac filter	1.3 Ω

STEADY-STATE LINE REGULATION OF UPSs

We also measured the steady-state voltage regulation of the two uninterruptible power supplies; the results are shown in Fig. 15. The 35 Ω load connected to each UPS during these tests represents the maximum rated load.

An internal relay connected the input and output terminals of the Topaz standby UPS until the input voltage declined to 102.2 V rms. At that point the relay connected the output terminals to a sine-wave inverter that was powered by internal lead-acid batteries. When the relay changed state, the output voltage increased from 102 V rms to 121 V rms, an increase of 19 V rms.

Because of the 102 V rms switch point, the UPS output voltage may be too low for some critical loads. If this is the case, a line conditioner could be connected downstream from the standby UPS to boost the rms voltage. Or, if extended brownouts with a mains voltage below the UPS switchpoint occur, a line conditioner could be connected upstream from the standby UPS to boost the rms input voltage to the UPS. Alternately, the standby UPS could be adjusted to switch at, for example, 108 V rms. However, the choice of a greater switch point increases the risk that the UPS will drain its batteries during a brownout. Line conditioners or voltage regulators, not a UPS, should be used to correct brownouts.

When the rms value of the input to Topaz standby UPS increases to 109 V, the relay changes state and the output and input are again

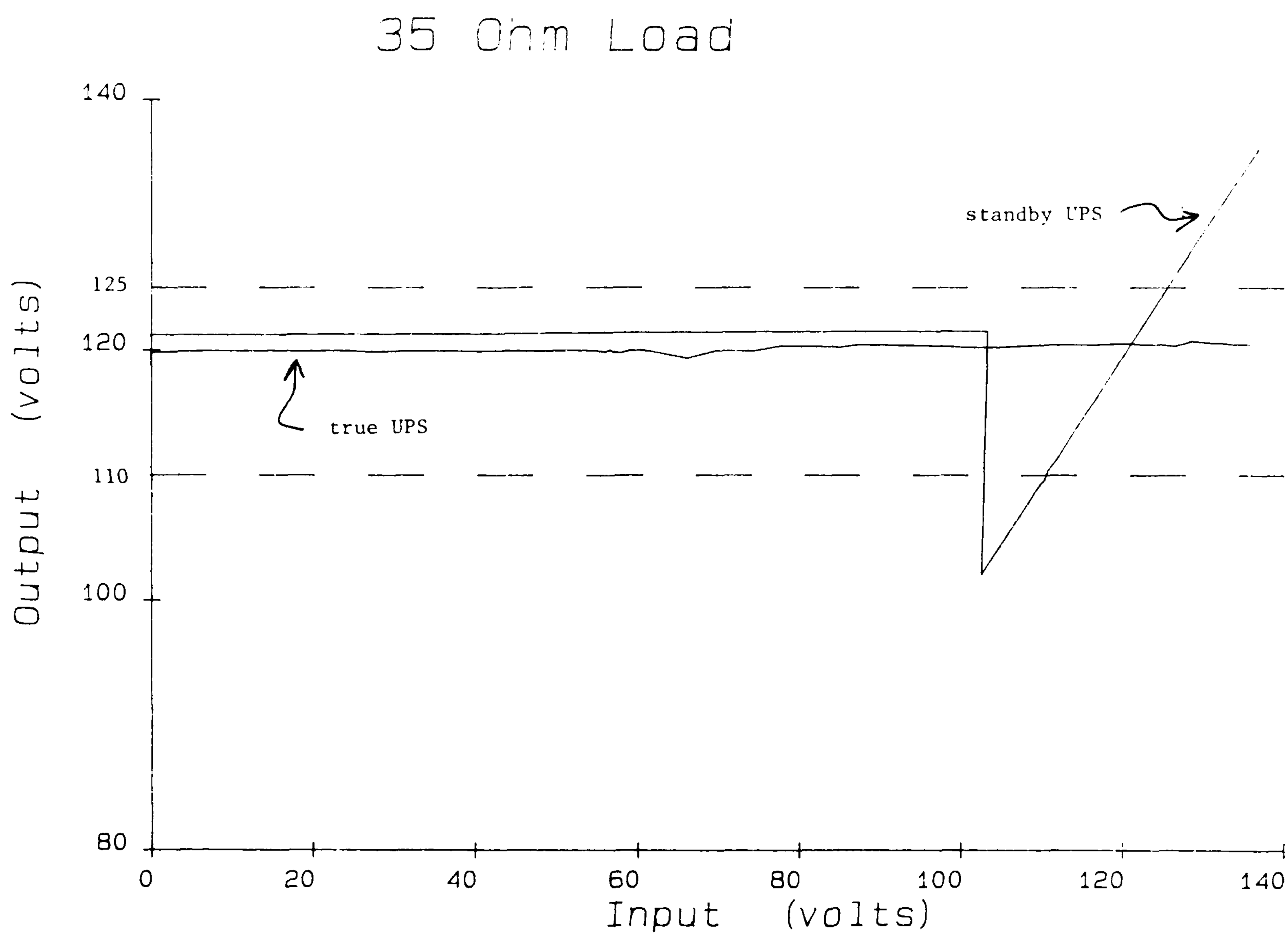


Figure 15. Rms output voltage as function of input voltage for two types of UPSs with a 35 Ω load.

directly connected. There is 7 V rms hysteresis between the two switching points on the input.

The Deltec UPS was chosen as an example of a "true UPS." In a true UPS the output terminal is always connected to the output of the sine-wave inverter circuit (provided that either the batteries are charged or the rms mains voltage is in an acceptable range).

The Deltec UPS provided an essentially constant 120 V rms output over the range of input voltages between 0 and 136 V rms. A small decrease in output voltage was noted when the input voltage was decreased to about 66 V rms. This may be associated with the disconnection of the internal battery charging circuit. We noticed an audible noise came from the Deltec UPS when the input voltage was about 66 V rms.

The Deltec UPS was connected to the mains and operated without a load for about a month after these steady-state line regulation tests. No additional tests were performed during this one-month period. At the end of this period we noticed that the Deltec UPS failed to operate from its internal batteries. At all times when the Deltec UPS was connected to mains, external metal oxide varistors were used for protection from possible transient overvoltages. This UPS was returned to the factory for repairs. After being repaired, it failed again during routine service. This UPS was not subjected to further testing after its two failures.

SECTION 5

DYNAMIC LINE REGULATION TEST METHODS

We measured the ability of the line conditioners to maintain a constant rms output voltage when the input voltage was suddenly switched from 116 V rms to 90 V rms.

Dynamic line regulation tests were performed on two line conditioners. The schematic drawing for the tests is shown in Fig. 16. One input voltage is provided by an autotransformer that is rated to supply 10 A rms at 0 to 140 V rms. This autotransformer was operated at less than half of its maximum output current in order to reduce effects of loading on output voltage. The other input voltage was supplied by direct connection to the power line, which had a typical value of 117 V rms.

The switching was done with an electromechanical relay. The relay often produced noise for durations of 3 to 10 ms, which was useful to observe the performance of the low-pass filter inside each line conditioner. Such noisy switching may be typical of field applications. In all schematics in this report the relay is shown in its initial (t = 0) state.

The input and output voltage of the equipment under test as a function of time was measured with a Tektronix 7612D digitizer with two Tektronix 7A13 differential amplifiers.

The differential-mode input voltage was obtained with two Tektronix 100X probes, one model P6007 and one model P6009. These two probes were properly compensated in the usual way with a 100 Hz square wave. The two probes were then connected to a 30 V peak-to-peak square wave with a frequency of 100 Hz. The compensation of the P6007 probe that was connected to the inverting input of the 7A13 amplifier was then adjusted to give the maximum common-mode rejection ratio (CMRR). We were able to obtain a CMRR value of -41 dB.

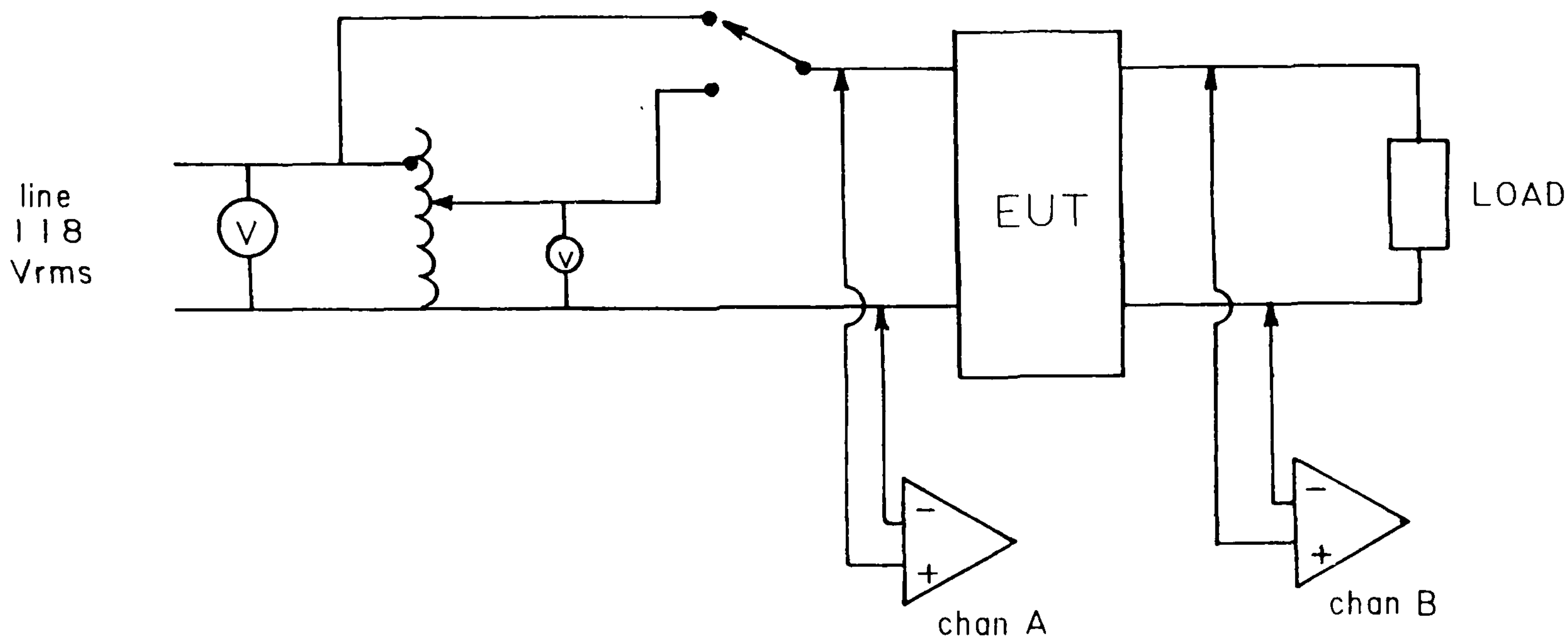


Figure 16. Dynamic line regulation test. The autotransformer was adjusted to give 90 V rms; the mains provided 116 V rms.

The differential-mode output voltage was obtained with two Tektronix P6015 probes. These probes were compensated in the same way as the 100X probes, as described above. We were able to obtain CMRR values of -38 dB with 100 Hz square waves and -58 dB at DC.

These probes were compensated at relatively low frequencies because the regulation experiments involved times of the order of 0.02 s to 0.7 s. An interval of 0.12 s was particularly common.

The digitizer took 2048 samples at a constant rate simultaneously from each of the two channels. The rate was variable from 200 samples per microsecond to 1 sample per second, although we always used a rate of at least 3300 samples per second. The digitizer has 8 bits full scale, which is better vertical resolution than conventional analog oscilloscopes provide. The digital record is also easier to analyze and plot for publication than a photograph of an analog oscilloscope's display.

The digitizer was set to provide several hundred pre-trigger samples. This delay, along with the response time of the relay, allowed at least one complete cycle of the waveform to be recorded before the relay changed state.

In all of the plots in this report Channel A of the digitizer is shown directly above the plot of Channel B. This allows convenient correlation of the test schematic with the plots of data.

Immediately before each data set was taken, power was disconnected from the test fixture and a blank record was digitized. The blank record was subtracted from the test data so that the location of the zero volt reference was established.

An IBM PC-XT desktop computer was used to acquire data from the Tektronix digitizer and store it on magnetic disks.

The dynamic line regulation was measured with each of the following loads:

1. 35 Ω resistor,
2. 75 Ω resistor,
3. 150 Ω resistor,
4. 15 μF capacitor,
5. 1/12 horsepower motor with no mechanical load.

For brevity only the results for the 35 Ω resistive load are shown, unless an interesting effect was observed with another load.

Of the devices purchased for these tests, dynamic regulation measurements were made only with the Sola ferroresonant line conditioner and the Topaz tap-switching line conditioner. The Deltec tap-switching line conditioner was not tested because it failed to operate with a capacitative load in the steady-state line regulation tests described above. The Oneac device was not tested for dynamic voltage regulation because it had no regulating properties, as shown in the steady-state tests described in the previous section.

At the completion of this research project we had 408 data files. We organized this large amount of data as it was collected by adopting a file name convention that indicated the major test conditions. Each file name is a sequence of four letters and two digits. The significance of the four-letter code is explained in Table 3. The file names are included with the figure numbers in the text of this report and are printed at the top of each figure. This provides positive identification of each figure.

TABLE 3. FILE NAME CONVENTIONS

File name format: ddtl##

where:

<u>dd</u> denotes device under test

DE - Deltec Tap-Switcher

ON - Oneac Device

SO - Sola Ferroresonant

TO - Topaz Tap-Switcher

TU - Topaz UPS

XX - no EUT in circuit

<u>t</u> denotes the type of test performed

A - Startup

B - Shutdown

C - Line Regulation (90 V rms → 116 V rms)

D - Load Regulation

E - Line Regulation (116 V rms → 90 V rms)

F - Line Regulation (examine tap-switching)

R - Differential-Mode Ringwave

S - Common-Mode Ringwave

T - Differential-Mode 8x20 μs Waveform

U - Common-Mode 8x20 μs Waveform

W - Differential-Mode "EMP Waveform"

X - Common-Mode "EMP Waveform"

Y - Differential-Mode Large Pulse

Z - Common-Mode Large Pulse

<u>l</u> denotes the type of load

A - no load

B - 35 Ω resistor

C - 15 μF capacitor

F - 1/12 hp motor

G - 75 Ω resistor

H - IBM PC/XT computer

J - HP 9836 computer

K - 150 Ω resistor

P - 15 μF cap. switched to 1/12 hp motor

Q - no load switched to 35 Ω resistor

S - 35 Ω resistor switched to no load

is a two-digit number that starts at zero and is incremented by one for each successive file that was collected with the same four-letter part of the name.

DYNAMIC LINE REGULATION TEST RESULTS

Dynamic line regulation test results for the Sola ferroresonant and Topaz tap-switching line conditioners are shown in Figs. 17 and 18 (files SOEB00 and TOEB00), respectively. Notice the noise that appeared on the input side in Fig 17 (file SOEB00) was greatly attenuated by the ferroresonant transformer. The input waveform was less than 90 V rms during the 8.2 ms switching interval. This produced a decrease in the rms output voltage during this interval.

In contrast, the tap-switching line conditioner passed the switching disturbance between 46 and 50 ms in Fig. 18 (file TOEB00). The reduction in rms input voltage caused the tap-switching control electronics to cease functioning between 63 and 96 ms.

The digitizer sample rate was increased from 16.7 samples per millisecond to 100 samples per millisecond in order to show the details of the switching transient with the ferroresonant line conditioner. The results are shown in Fig. 19 (file SOCB02). There is a burst of transients on the input of at least 400 V peak to peak at 8.4 ms. These transients are attenuated at the output of the ferroresonant transformer to 35 V peak to peak. The digitizer clipped the input voltage transients at its full scale values of ±200 V. In Fig. 19 (file SOCB02) notice that the rms input voltage was changed

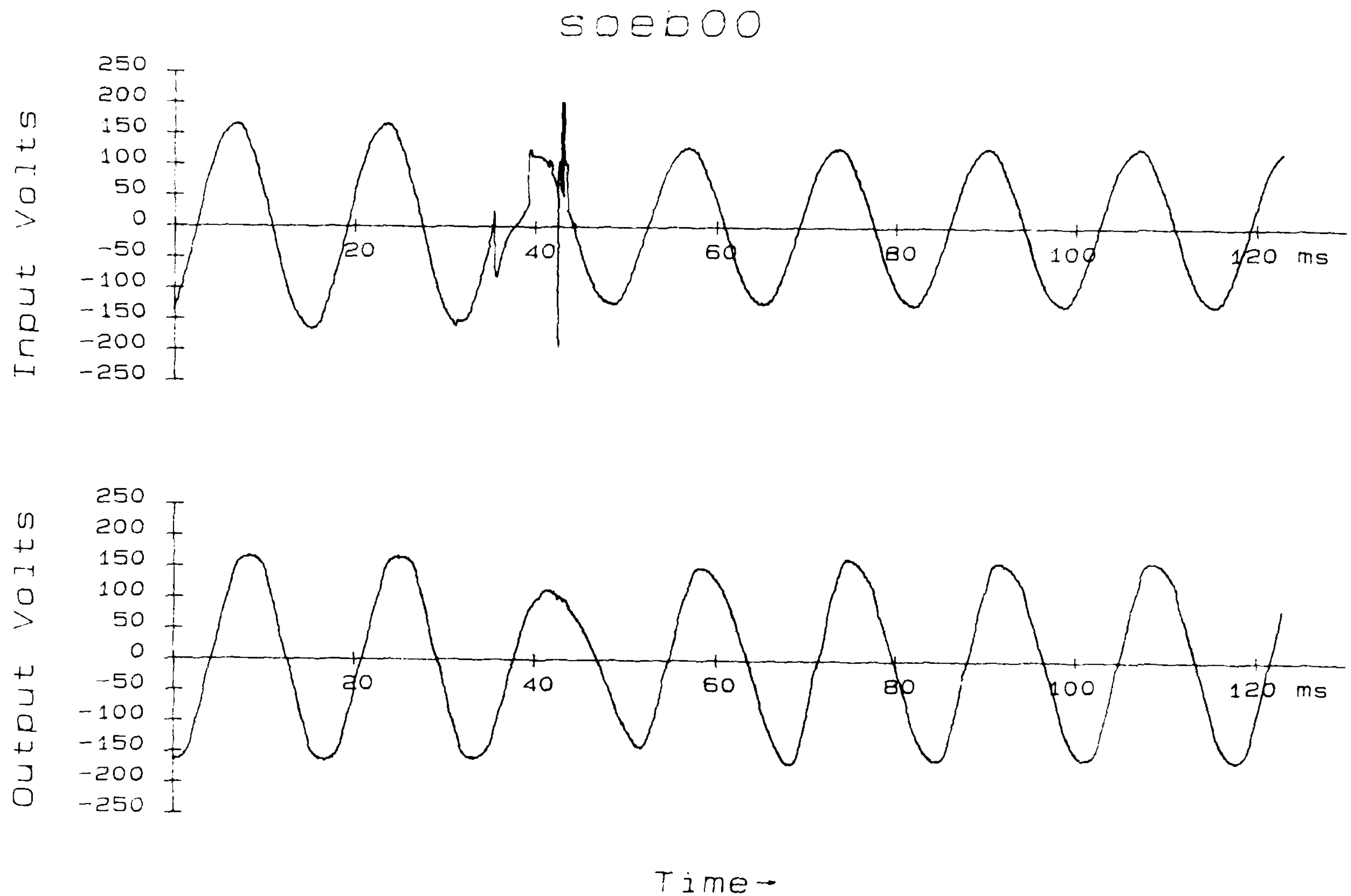


Figure 17. Dynamic line regulation test of a Sola ferroresonant conditioner with a 35 Ω load. The input voltage was switched from 116 V rms to 90 V rms.

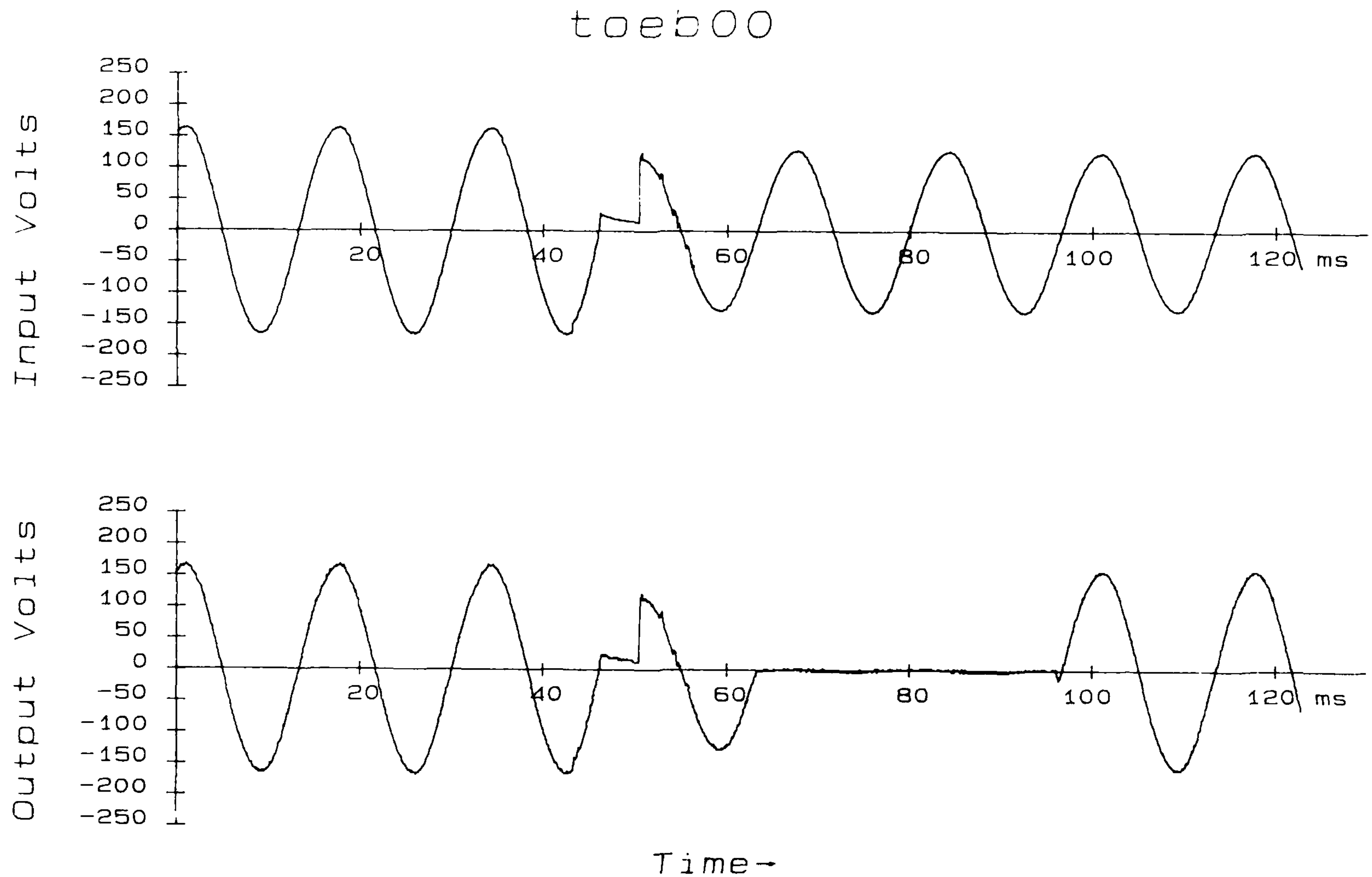


Figure 18. Dynamic line regulation test of a Topaz tap-switching conditioner with a 35 Ω load. The input voltage was switched from 116 V rms to 90 V rms.

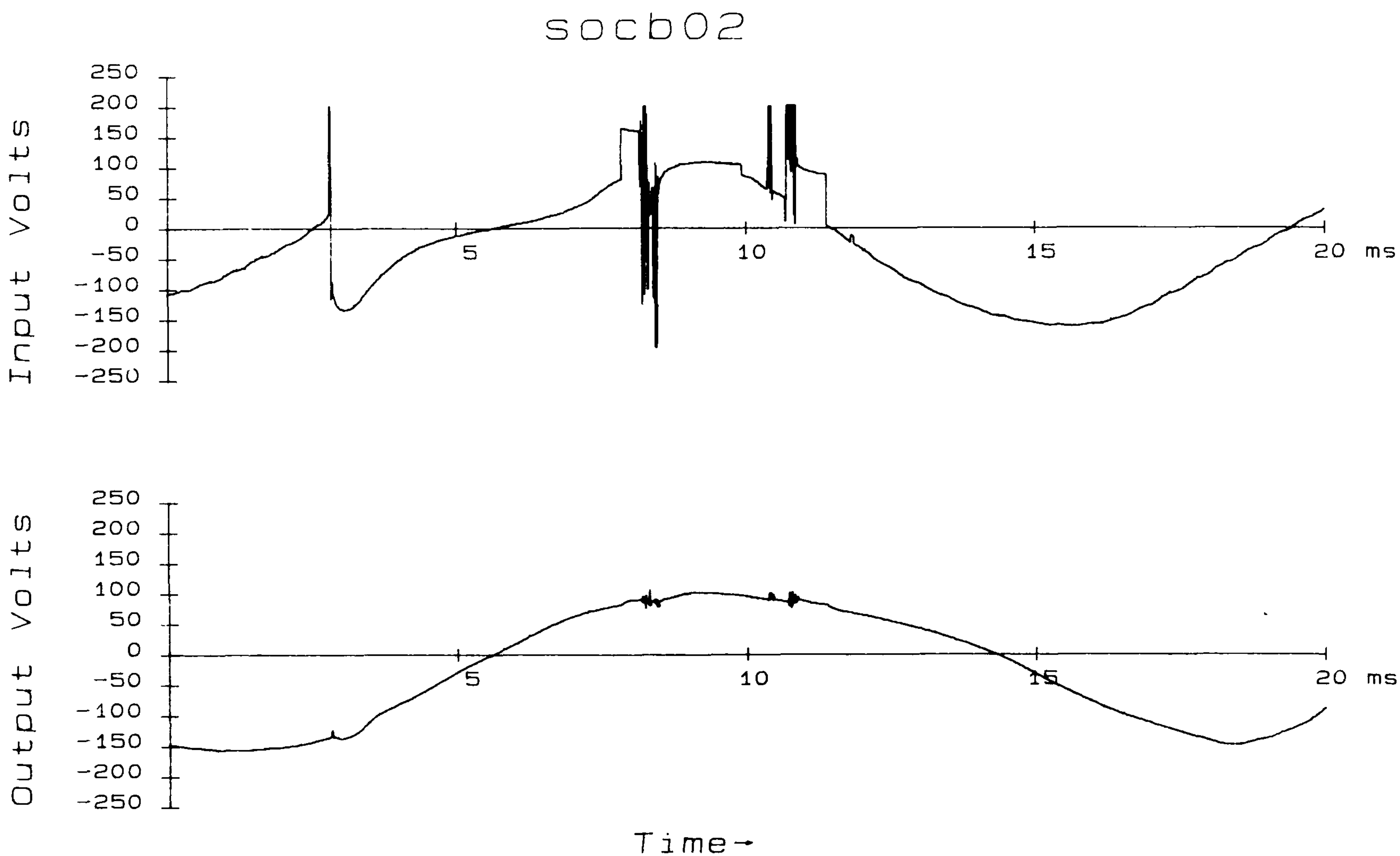


Figure 19. Dynamic line regulation test of a Sola ferroresonant conditioner with a 35 Ω load. The input voltage was switched from 90 V rms to 116 V rms.

from 90 to 116 V, the reverse order of the other plots in this section. Whether the larger rms input voltage came before or after the switch made no difference on the behaviaor of the output voltage.

When a 150 Ω load resistor was substituted for the 35 Ω load in the previous tests, the results in Figs. 20 and 21 (files SOEKOO and TOEKOO) were obtained. Figure 20 (file SOEKOO) shows the ability of the ferroresonant's transformer to attenuate switching noise. In contrast, the switching transient between 36 and 40 ms in Fig. 21 (file TOEKOO) is passed to the output of the tap-switching line conditioner. The tap-switching line conditioner does not cease to function in Fig. 21 (file TOEKOO), as it did in Fig. 18 (file TOEBOO), probably because it is not as heavily loaded.

The results of the dynamic line regulation with a motor load are shown in Figs. 22 and 23 (files SOEFOO and TOEFOO). In Fig. 22 (file SOEFOO) there are three positive peaks of 200 V on the input. The actual size of these peaks is probably larger, since the digitizer reached its full scale value at ±200 V. Only the middle peak appeared at the output of the ferroresonant transformer; the output peak is only 160 V. In Fig. 23 (file TOEFOO) the switching transient is shown to pass through the tap-switching line conditioner.

DYNAMIC LOAD REGULATION TEST METHODS

The dynamic load regulation tests used a relay to switch the load impedance from one value to another while the output voltage and current were measured. The rms input voltage was kept constant during these tests. The schematic diagram is shown in Fig. 24.

The load current was measured with a Tektronix model P6021 current transformer and model 134 amplifier. The P6021 current transformer was connected to the load with a Tektronix CT-5 current probe set to 20X attenuation. The CT-5 probe allowed the P6021 current transformer to be able to measure larger currents. The manufacturer's specifications for the CT-5, P6021, and 134 amplifier

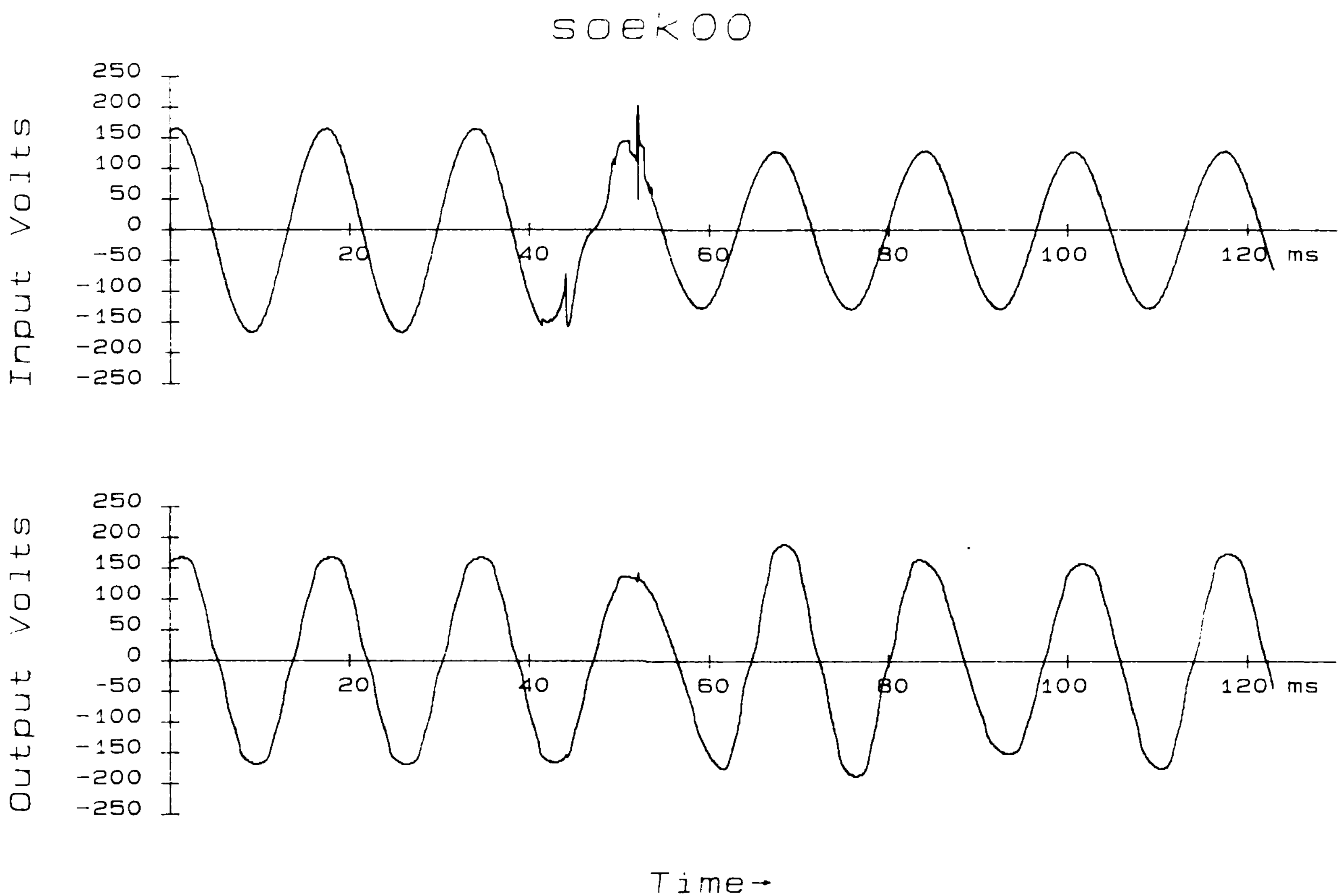


Figure 20. Dynamic line regulation test of a Sola ferroresonant conditioner with a 150 Ω load. The input voltage was switched from 116 V rms to 90 V rms.

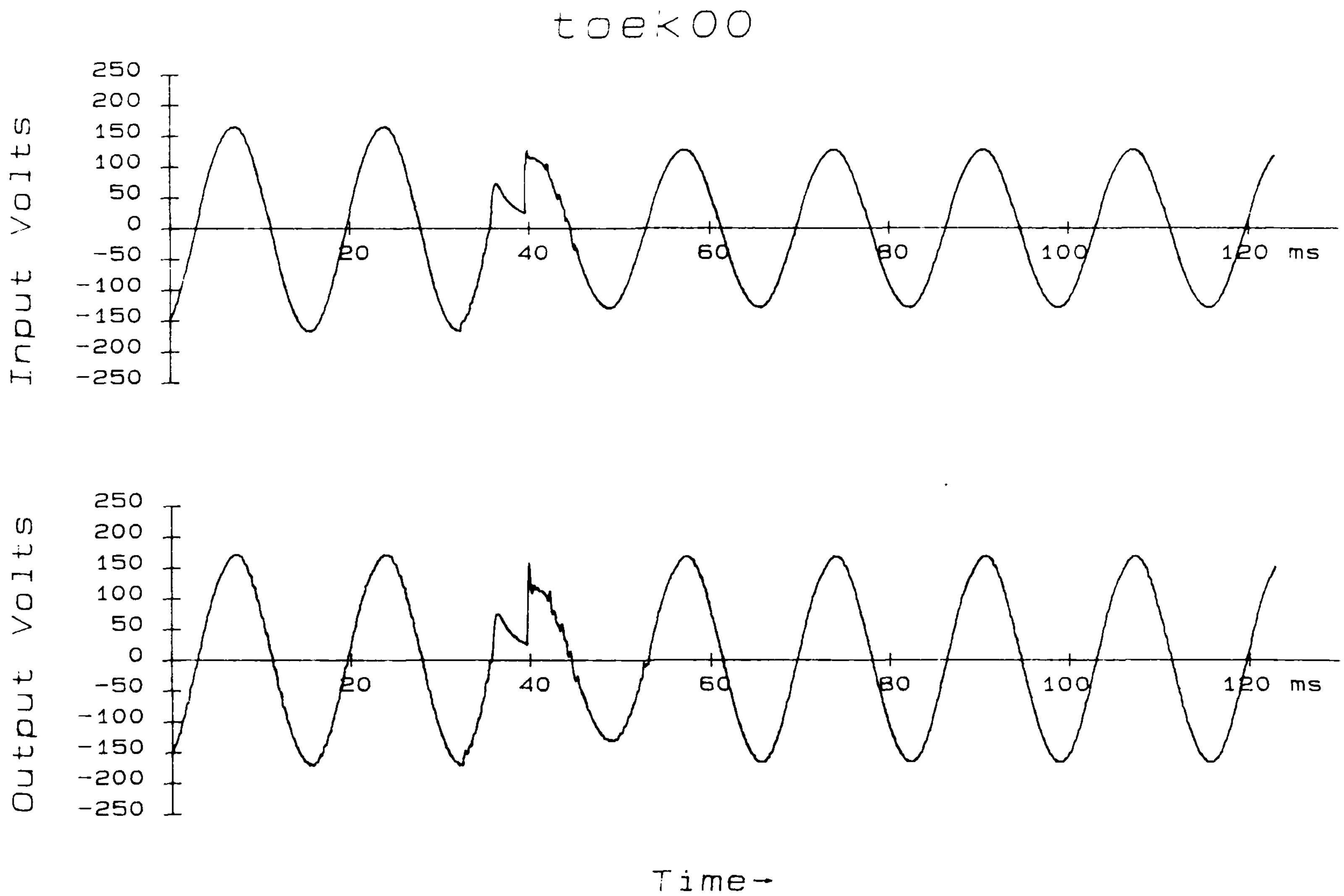


Figure 21. Dynamic line regulation test of a Topaz tap-switching conditioner with a 150 Ω load. The input voltage was switched from 116 V rms to 90 V rms.

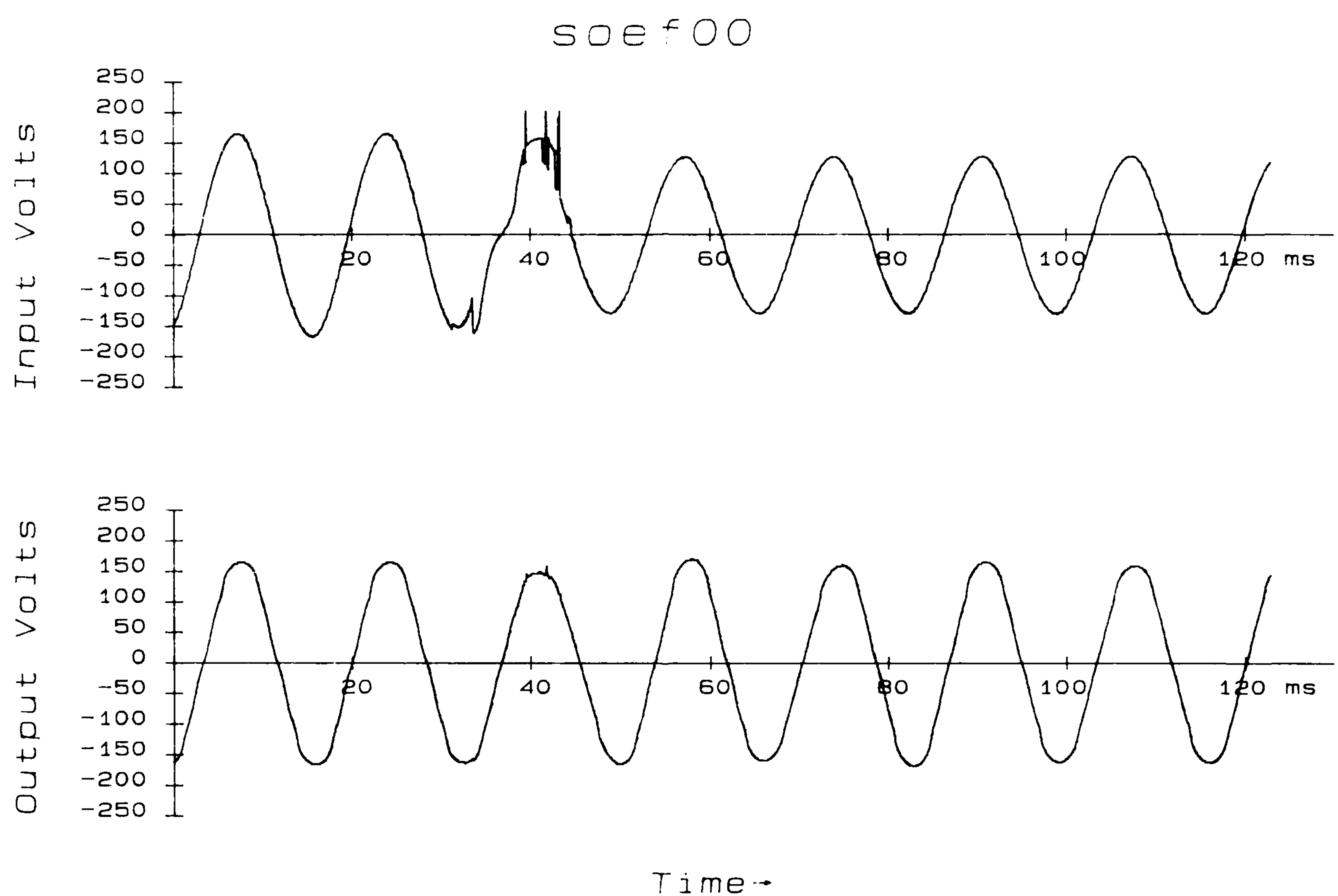


Figure 22. Dynamic line regulation test of a Sola ferroresonant conditioner with a motor load. The input voltage was switched from 116 V rms to 90 V rms.

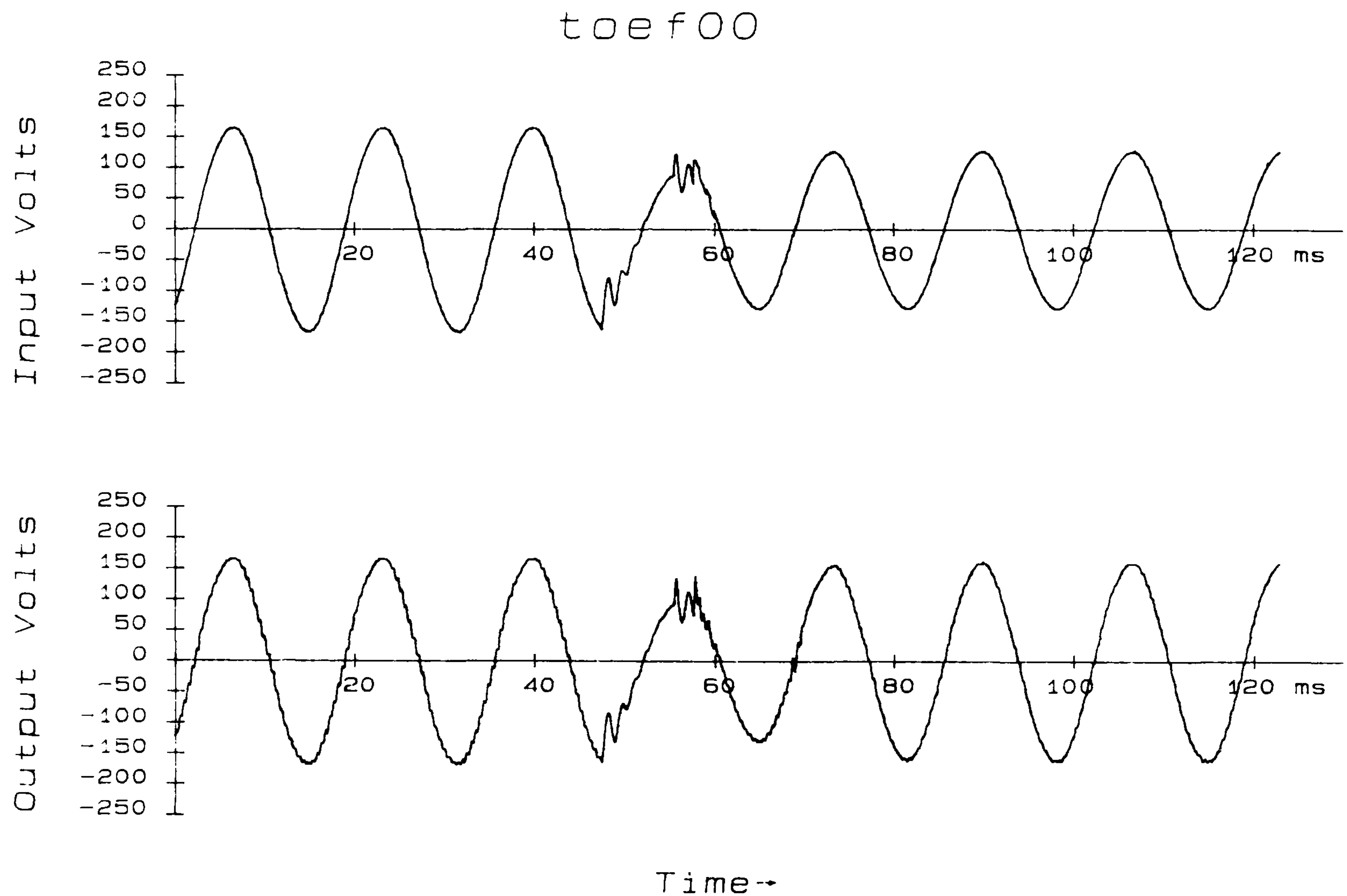


Figure 23. Dynamic line regulation test of a Topaz tap-switching conditioner with a motor load. The input voltage was switched from 116 V rms to 90 V rms.

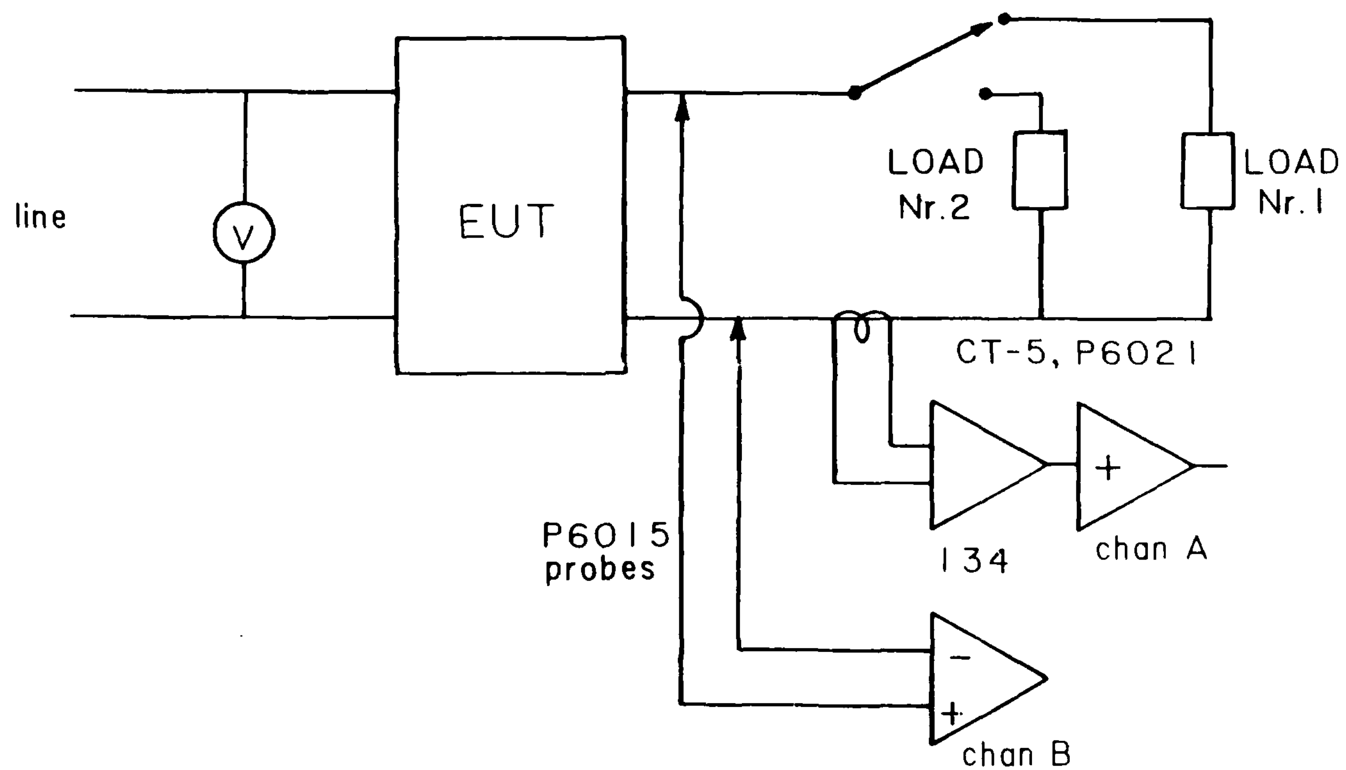


Figure 24. Dynamic load regulation test.

give a bandwidth of 12 Hz to 20 MHz. The magnetic field produced by the current in the circuit is coupled to the CT-5 and P6021 probes; there is no electrical connection between the probes and circuit. The effect of the probes on the circuit is approximately equivalent to inserting a resistance in the circuit of less than 0.02 Ω, a trivial value compared to the load impedance.

The P6015 probes, 7A13 amplifiers, and digitizer are the same as described above for the dynamic line regulation tests.

The equipment under test (EUT) in Fig. 24 was either a Sola ferroresonant line conditioner or a Topaz tap-switching line conditioner.

DYNAMIC LOAD REGULATION TEST RESULTS

In Fig. 25 (file SODS02) the response of the Sola ferroresonant transformer is shown during switching of the load from 35 Ω to 75 Ω. When the 75 Ω load was connected at time 43.8 ms. the output voltage decreased by 140 V in a narrow notch. The relay disconnected both loads for 4 ms. Because of this long connection time, the change was really from no load to 75 Ω load. The output impedance of the ferroresonant transformer caused the momentary drop in output voltage when the output current increases from the no load to 75 Ω load condition. One sample was taken every 60 μs, which may not have been often enough to accurately measure the depth of this notch. The load current is not shown in Figs. 25 and 26 due to artifacts in these records.

The first positive and negative peaks of the output voltage after the 75 Ω load was connected had about 25 V greater magnitude than the four peaks prior to the change of load. Thereafter the output voltage was stable.

Figure 26 (file TODS02) shows the response of the Topaz tap-switching line conditioner to the same test as described for

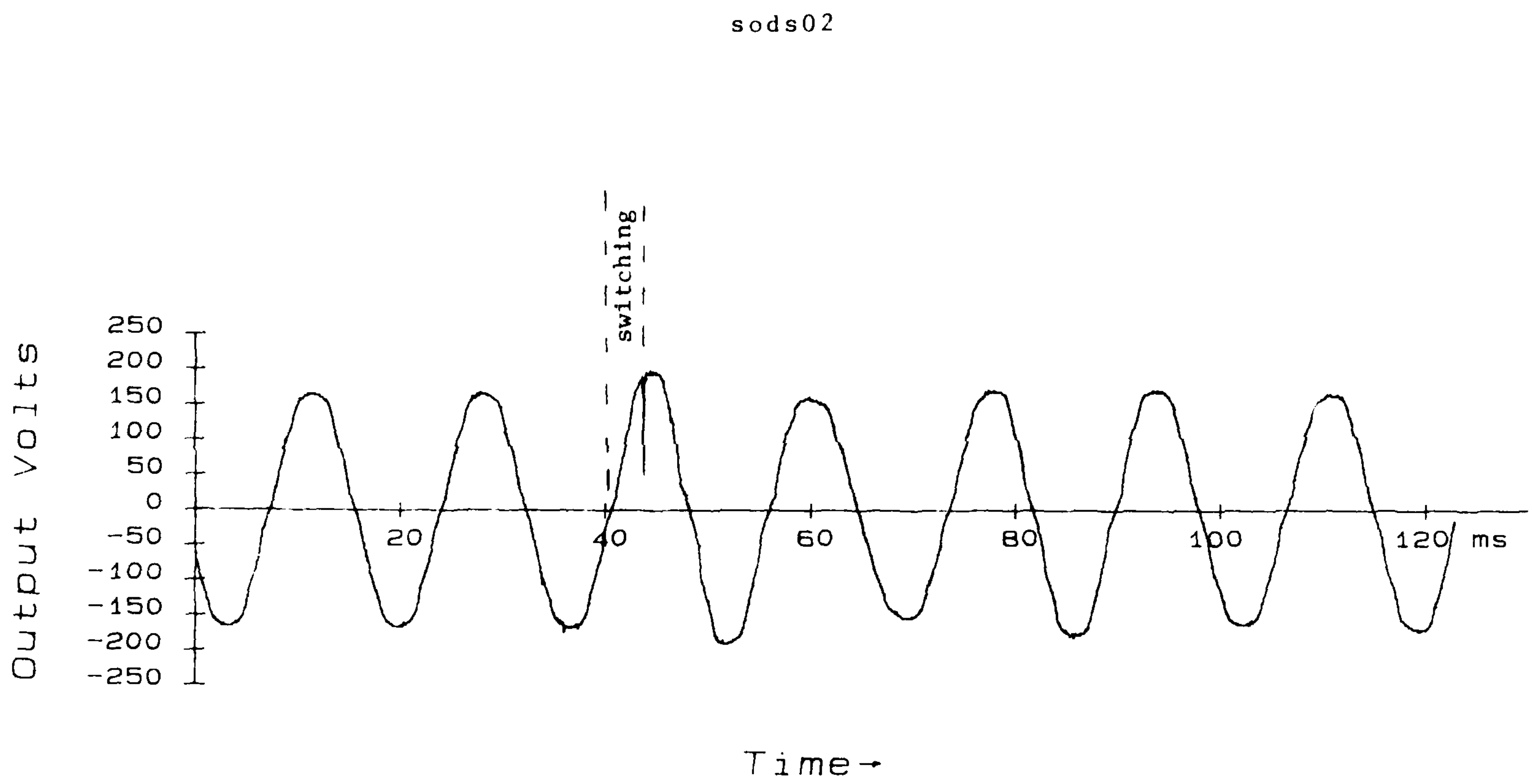


Figure 25. Dynamic load regulation test of a Sola ferroresonant conditioner. The load was switched from 35 Ω to 75 Ω.

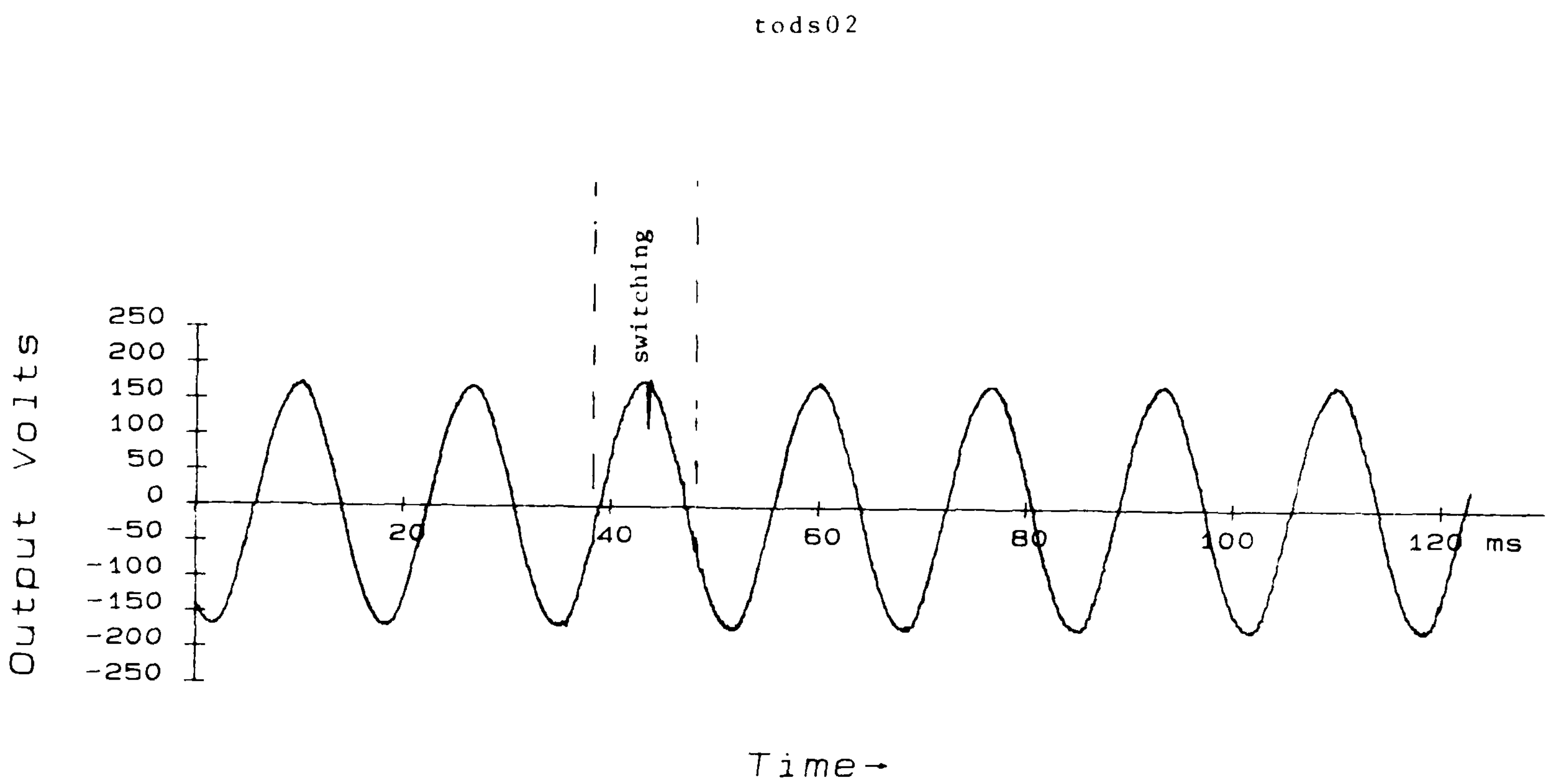


Figure 26. Dynamic load regulation test of a Topaz tap-switching conditioner. The load was switched from 35 Ω to 75 Ω.

Fig. 25 (file SODS02). The output voltage had a 70 V notch when the 75 Ω load was connected. One sample was taken every 60 μs, which may not have been often enough to accurately measure the depth of the notch.

The peaks of the output voltage have the same magnitude before and after the change of load for the tap-switching conditioner.

The response of the two different line conditioners to switching from a 15 μF capacitative load to a motor load is shown in Figs. 27 and 28 (files SODP01 and TODP01). The ferroresonant line conditioner cannot supply the large current required during starting the motor, which had no mechanical load. Consequently, the output voltage of the ferroresonant transformer was reduced for at least four cycles after the motor was connected. In contrast, the output voltage of the tap-switching transformer was stable one half cycle after the motor was connected.

STARTUP TEST METHODS

When line conditioners are switched on, they do not instantly provide regulated sine wave power. The startup tests, which are described in this section, monitored the input and output voltage of line conditioners when the mains were switched on. The test schematic is shown in Fig. 29. The equipment under test (EUT) is either a Sola ferroresonant line conditioner or a Topaz tap-switching line conditioner. The probes, amplifiers, and digitizers were described above in the dynamic line regulation section.

The relay was adjusted to switch when the mains voltage was about -125 V and had a positive slope.

STARTUP TEST RESULTS

The startup behavior of the Sola ferroresonant transformer with no load is shown in Fig. 30 (file SOAA00). The output voltage was

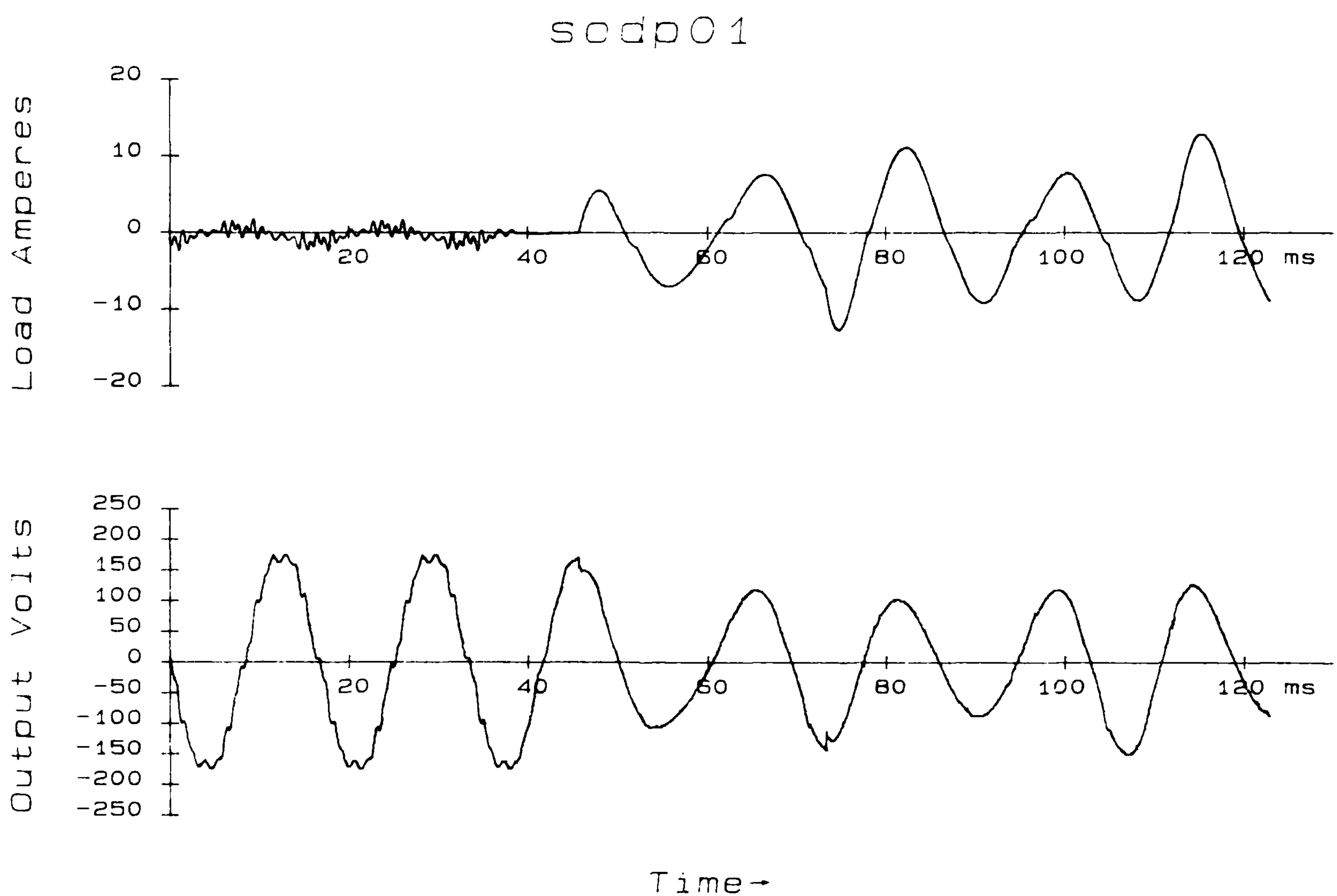


Figure 27. Dynamic load regulation test of a Sola ferroresonant conditioner. The load was switched from a 15 μF capacitor to a motor.

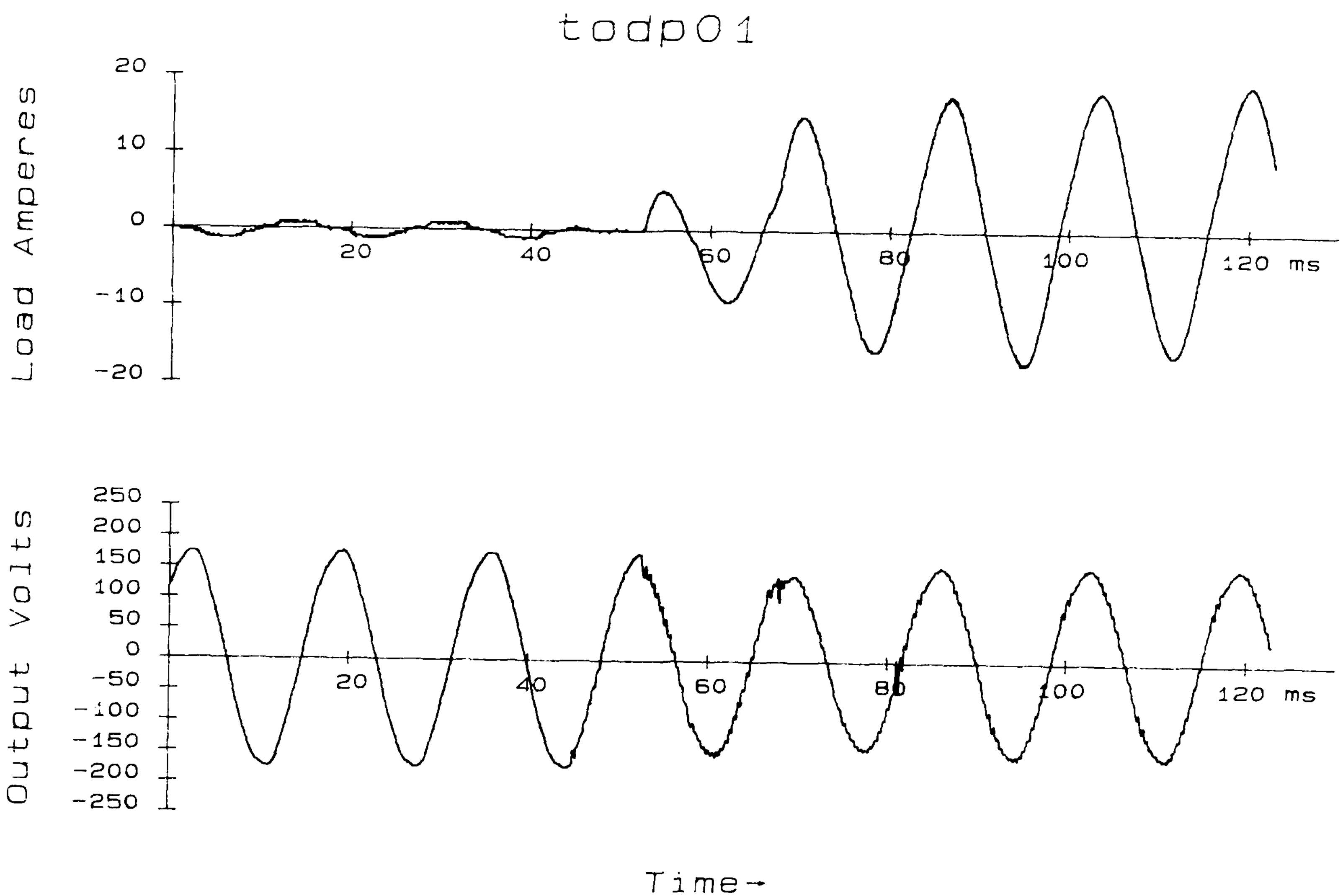


Figure 28. Dynamic load regulation test of a Topaz tap-switching conditioner. The load was switched from a 15 μF capacitor to a motor.

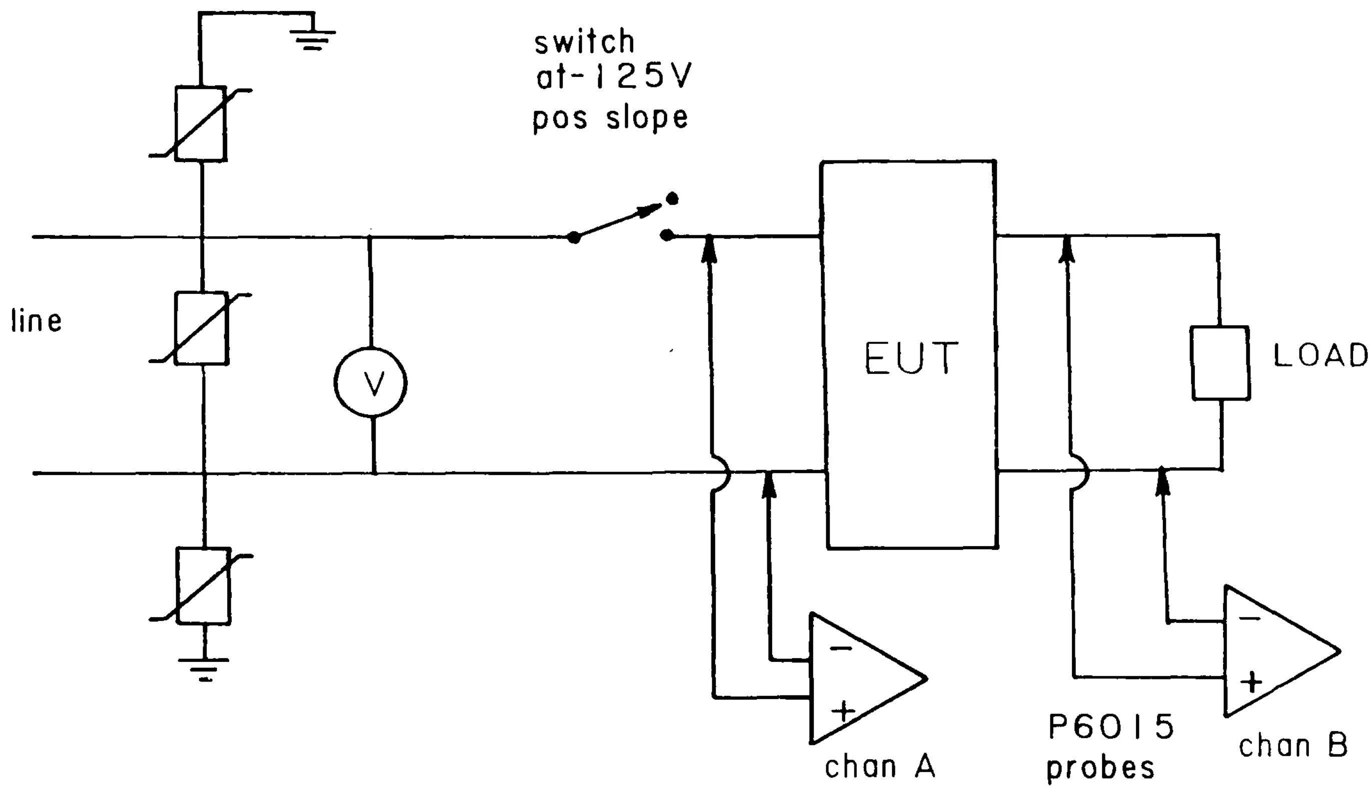


Figure 29. Startup tests.

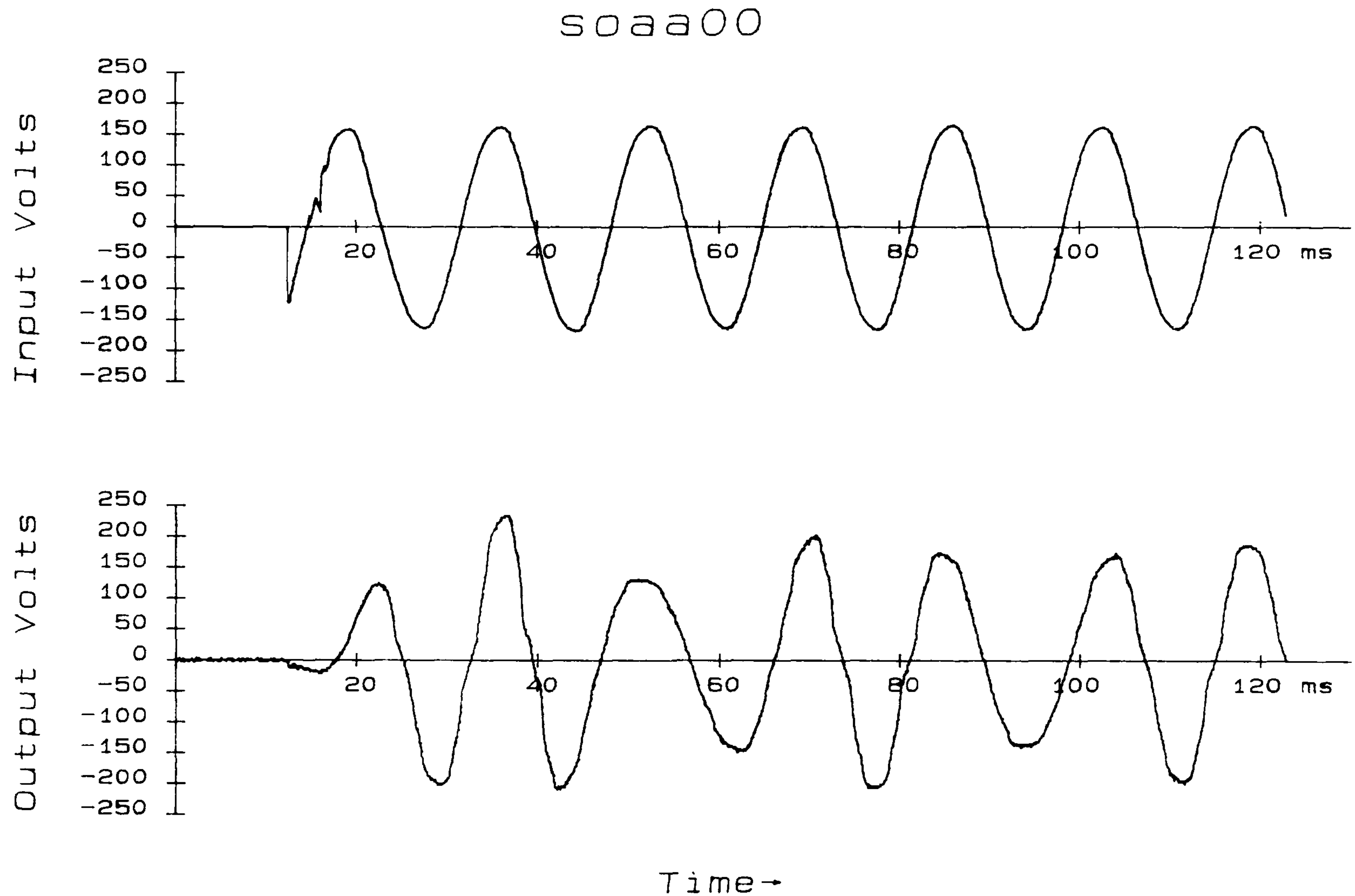


Figure 30. Startup test of a Sola ferroresonant conditioner with no load.

usable within one-half cycle of the turn-on time. However, the waveform was distorted and the amplitude fluctuated during at least the next five cycles.

The output voltage of the ferroresonant transformer with a 35 Ω load attached became stable within two cycles of the turn-on time, as shown in Fig. 31 (file SOAB00). Notice that the fluctuations of the input voltage due to bouncing of relay contacts did not appear at the output voltage of the ferroresonant transformer.

When the Topaz tap-switching line conditioner was switched on with no load, the output voltage was about 34 V rms for 333 ms, as shown in Fig. 32 (file TOAA00). With a 35 Ω load connected, the output voltage did not appear for 350 ms, as shown in Fig. 33 (file TOAB00). The initial 34 V rms sine wave that appeared when there was no load was attenuated by the 35 Ω load. After the 350 ms delay, the output voltage of the tap-switching conditioner appeared as a sine wave of the proper amplitude.

The delay time was the same for the 35 Ω load, the 15 μF capacitative load, and the 1/12 horsepower motor load. The Topaz tap-switching conditioner's normal output voltage appeared to begin at a phase angle of about -10 degrees of a sine function, regardless of load. This normal output appears about 350 ms after turnon.

SHUTDOWN TEST METHODS

The shutdown tests monitored the input and output voltages of the line conditioners when the mains were disconnected from the circuit.

The test schematic is identical to that used for the startup tests, except that the normally closed relay contact is now connected to the mains. The probes, amplifiers, and digitizer are described above in the dynamic line regulation section. The test schematic is shown in Fig. 34.

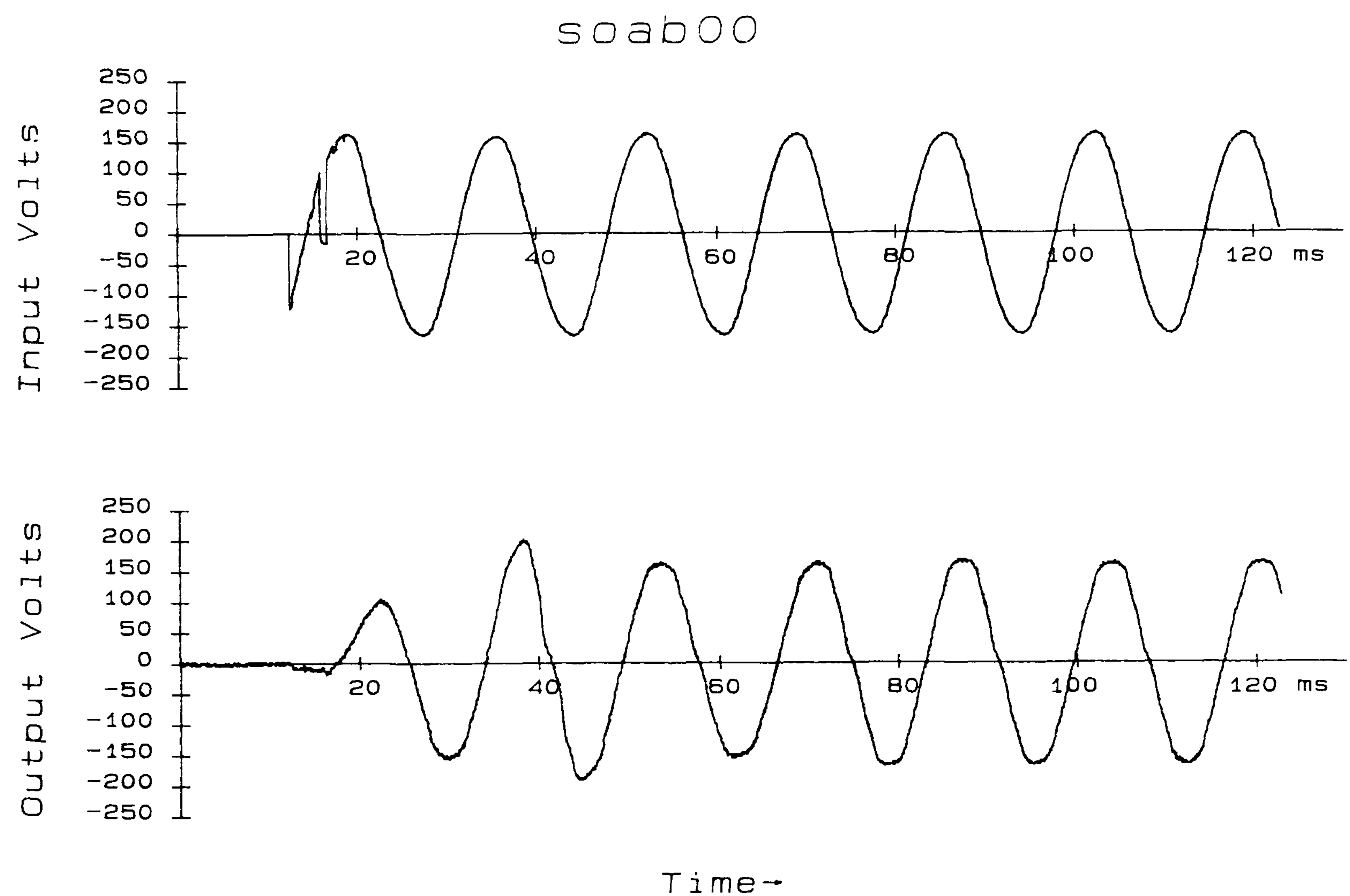


Figure 31. Startup test of a Sola ferroresonant conditioner with a 35 Ω load.

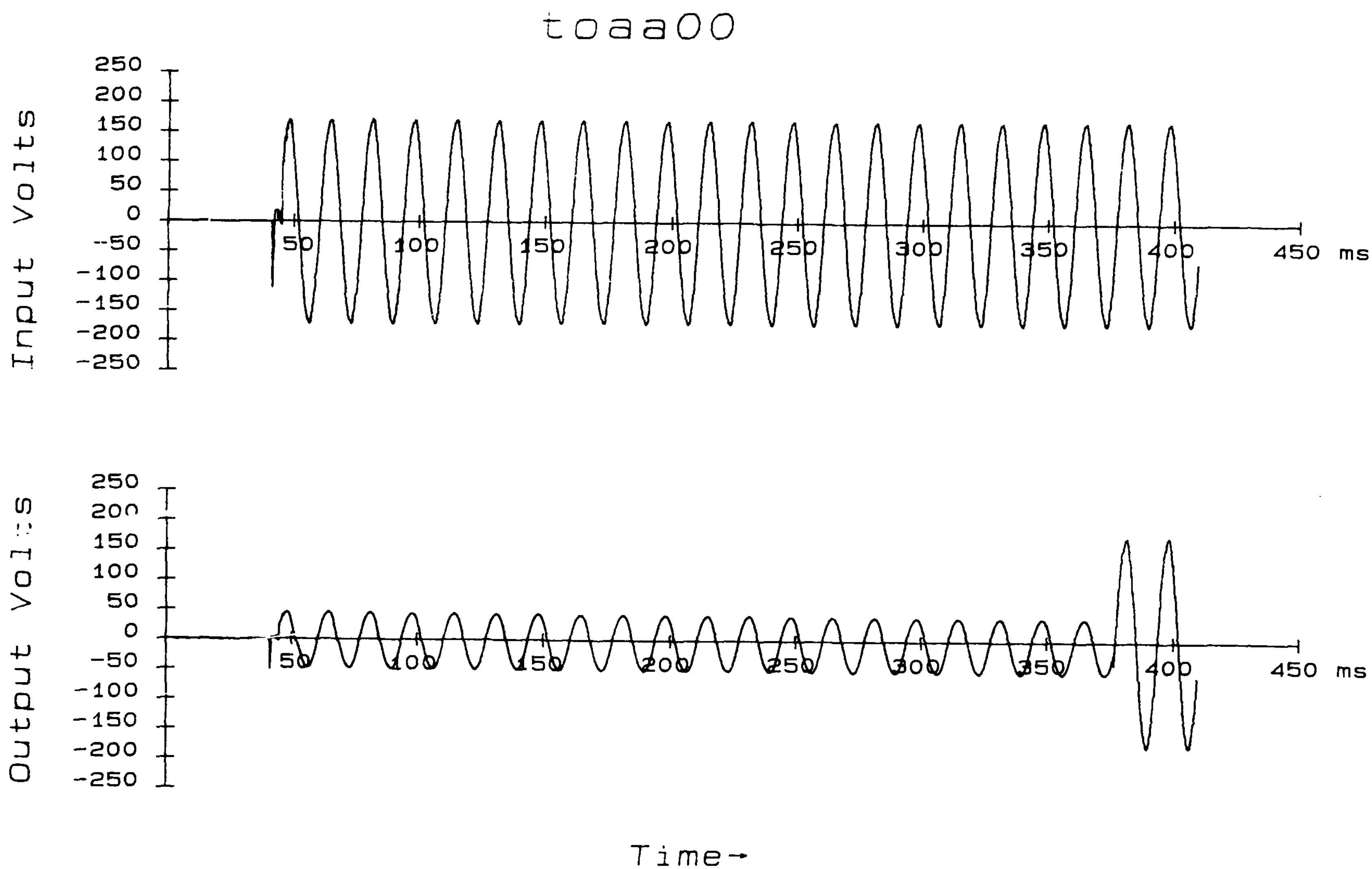


Figure 32. Startup test of a Topaz tap-switching conditioner with no load.

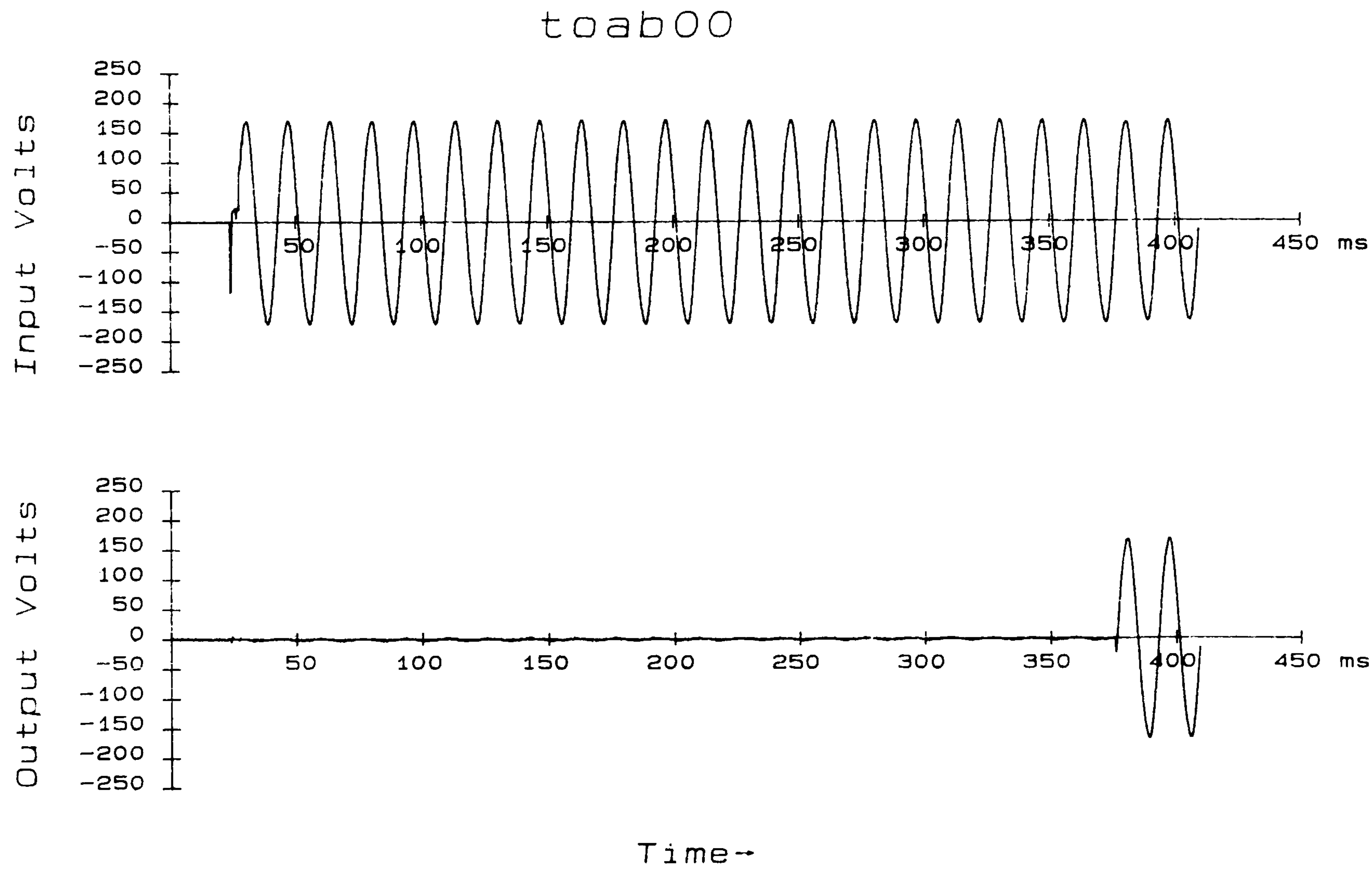


Figure 33. Startup test of a Topaz tap-switching conditioner with a 35 Ω load.

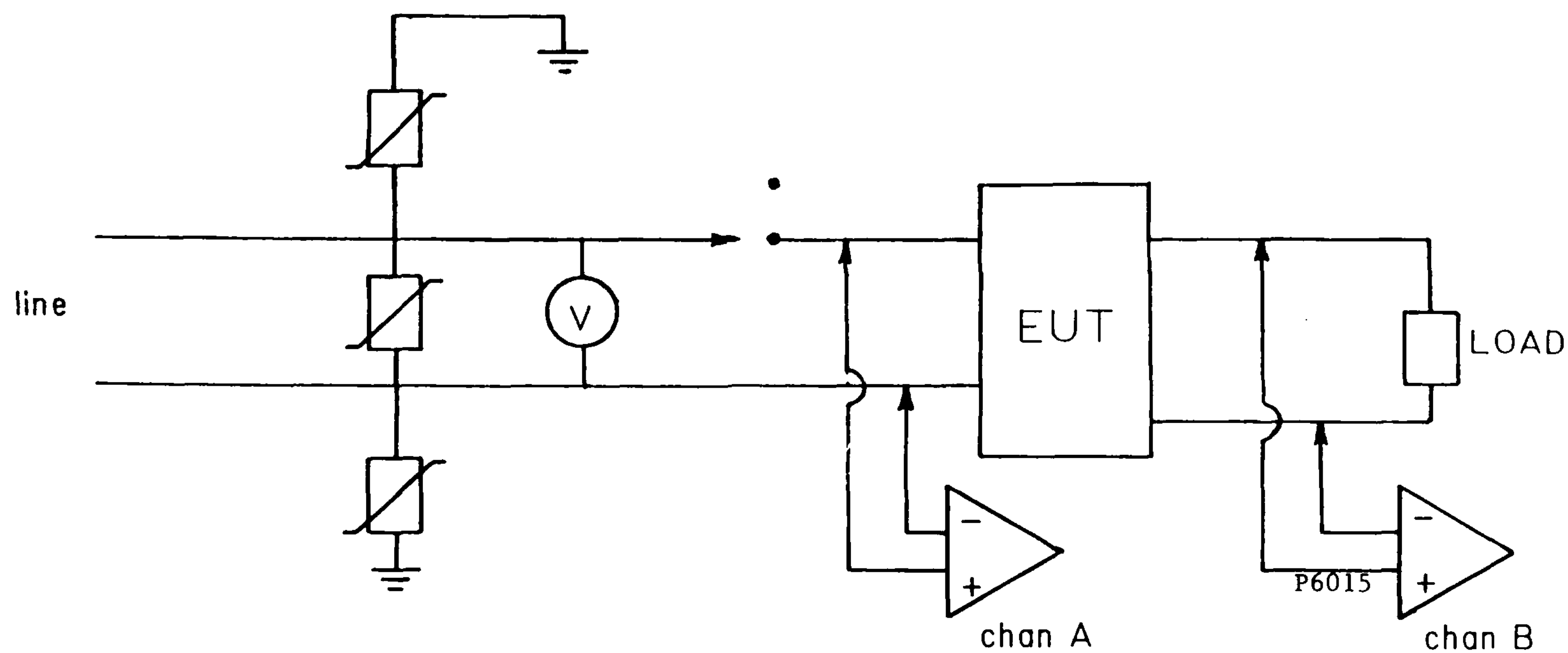


Figure 34. Shutdown tests.

SHUTDOWN TEST RESULTS

When no load is present, the output of the ferroresonant transformer continues to oscillate for many cycles after the mains are disconnected, as shown in Fig. 35 (file SOBA00). The amplitude of the output voltage declines approximately linearly with time between 41 and 150 ms. Notice that the frequency of the output waveform decreases after the mains are switched off. The last cycle shown in Fig. 35 (file SOBA00) has a frequency of 26 Hz instead of the 60 Hz frequency of the mains.

From the data presented it is apparent that the resonant output circuit of a ferroresonant transformer continues to supply power to the load during brief interruptions of the input (e.g., as were caused by bouncing of relay contacts).

Figure 36 (file SOBB01) shows the prompt decay of the output voltage of the ferroresonant transformer when a 35 Ω load is connected and the mains are switched off. The 35 Ω load is about 80% of the manufacturer's full-rated load.

The shutdown behavior of the ferroresonant conditioner was also observed with a 75 Ω load, which represents about 40% of the maximum rated load of the line conditioner. The results are shown in Fig. 37 (file SOBG00). The output voltage continues smoothly, although the amplitude decays linearly with time. The data in Fig. 37 ends abruptly at 122 ms. The data in this record were acquired at a more rapid sampling rate than in Figs. 35, 36, 38, and 39 but were plotted on the same scale.

In Figs. 35, 36, and 37 (files SOBA00, SOBB01, and SOBG00), notice that a voltage appears at the input terminals of the ferroresonant transformer after the mains have been disconnected. This voltage appears across an open-circuit. Notice that the waveform is not sinusoidal when no load or a 75 Ω load is present at the output of the transformer. When the 35 Ω load is present, the output voltage

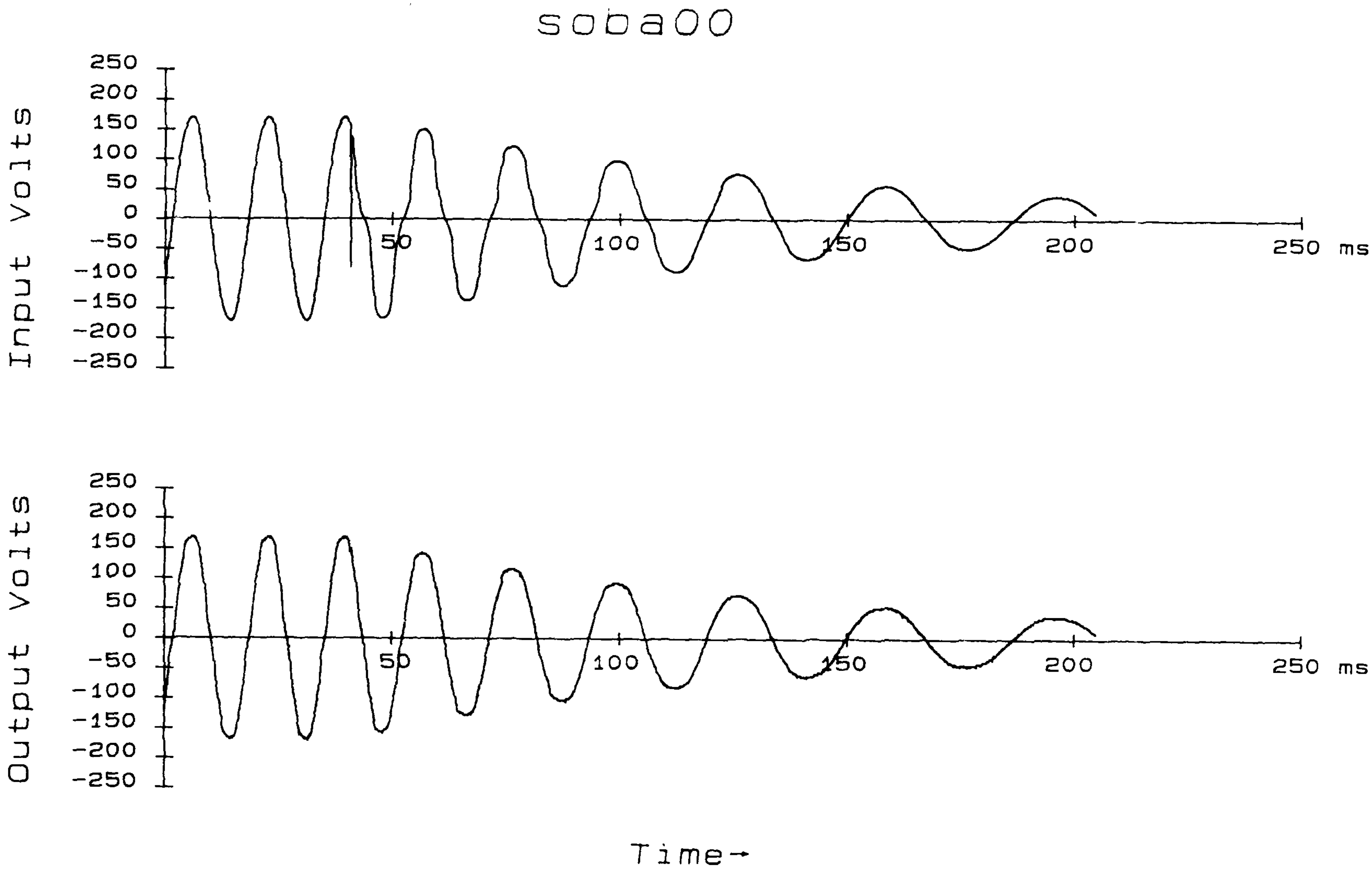


Figure 35. Shutdown test of a Sola ferroresonant conditioner with no load.

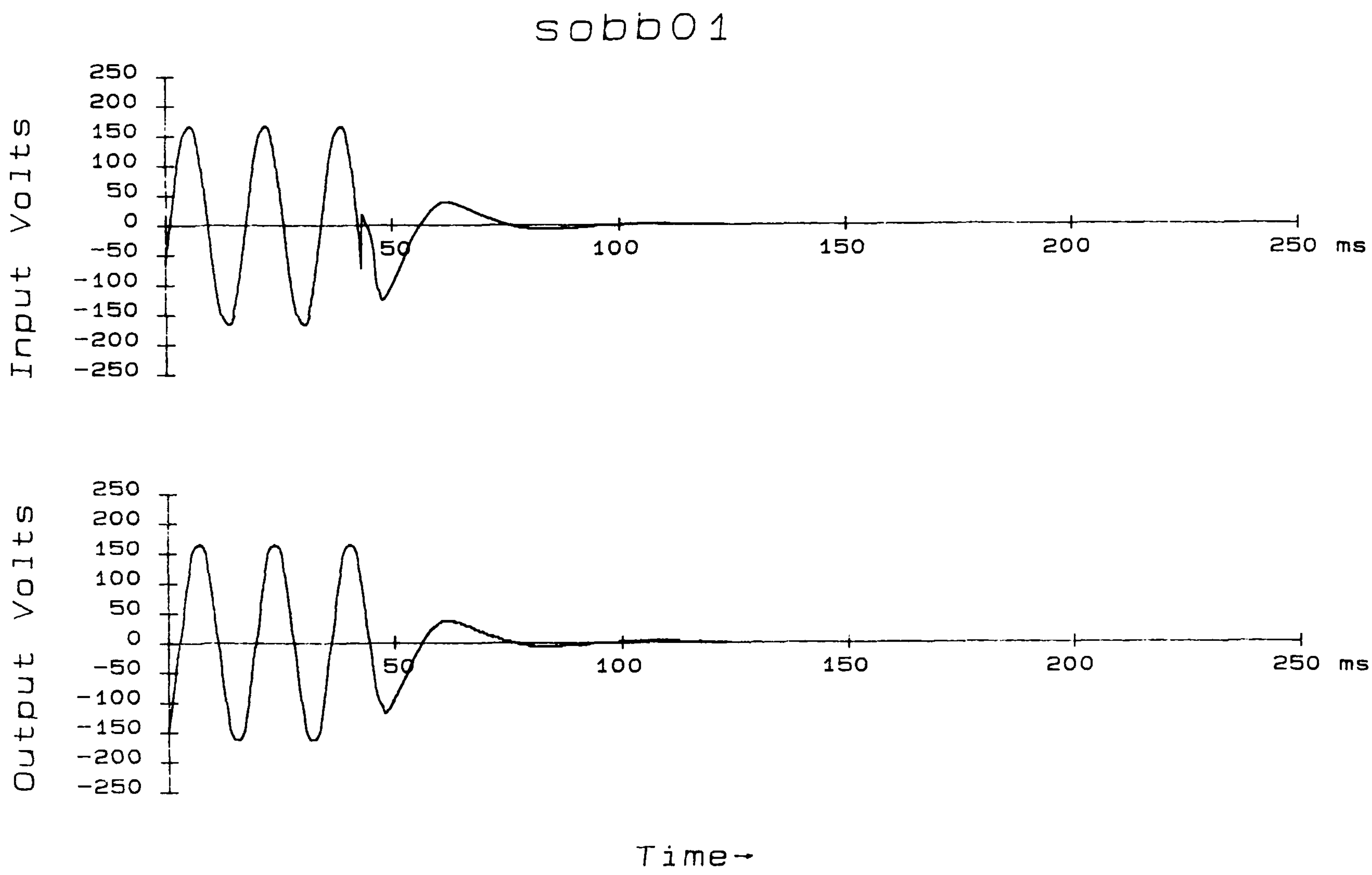


Figure 36. Shutdown test of a Sola ferroresonant conditioner with a 35 Ω load.

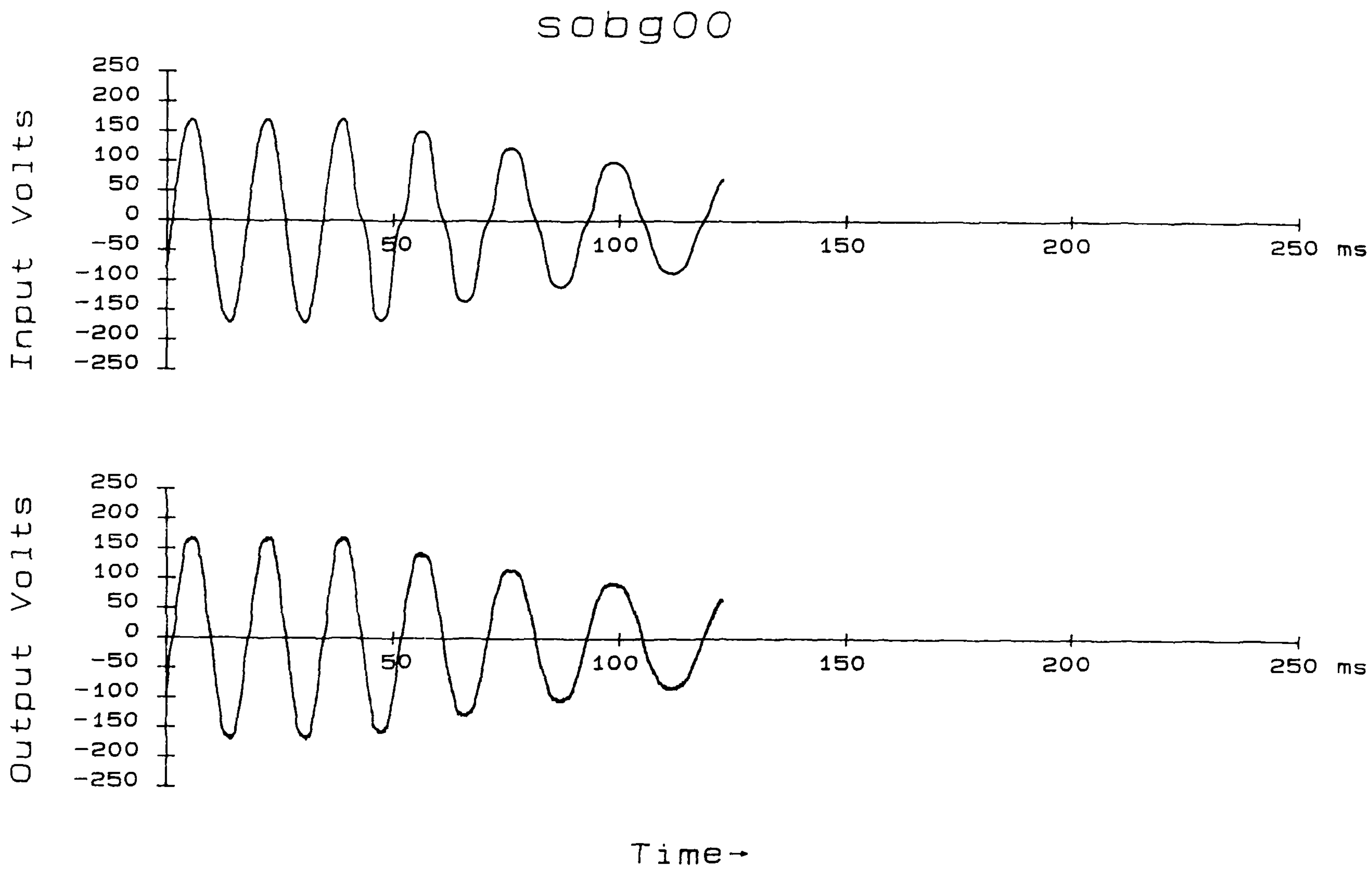


Figure 37. Shutdown test of a Sola ferroresonant conditioner with a 75 Ω load.

looks like the input voltage, except that the discontinuity due to relay switching is absent at the output.

When the mains were disconnected from the tap-switching conditioner, the output voltage decayed to negligible values very quickly, as shown in Figs. 38 and 39 (files TOBA00 and TOBB00) for no load and 35 Ω load, respectively. The input and output voltages have the same waveshape and values.

The most important point to be made in discussing the results of the shutdown tests is that the ferroresonant output circuit can continue to operate a load during an interruption of the mains for a few milliseconds, unlike the tap-switching conditioner.

The response of the Topaz standby UPS was measured when the mains were disconnected, Fig. 40 (file TUCB00). During this test a 35 Ω load, which was the manufacturer's maximum rated load, was present at the output of the UPS. The waveform at the output of the standby UPS took 2.6 ms to switch.

SHUTDOWN TRANSIENT

When the input voltage of the ferroresonant transformer was interrupted, a high voltage transient appeared on the input side of the transformer. This phenomenon is shown in Figs. 17, 19, 20, and 22 (files SOEB00, SOCB02, SOEK00, and SOEF00) above. To study this phenomenon, a second ferroresonant line conditioner was connected upstream from the equipment under test (EUT) and the relay, as shown in Fig. 41. This second ferroresonant transformer provided isolation and prevented the varistors across the mains from clamping the input voltage of the EUT. The second ferroresonant transformer had a maximum load rating that was 50% larger than the rating of the equipment under test. This prevented the second transformer from being overloaded.

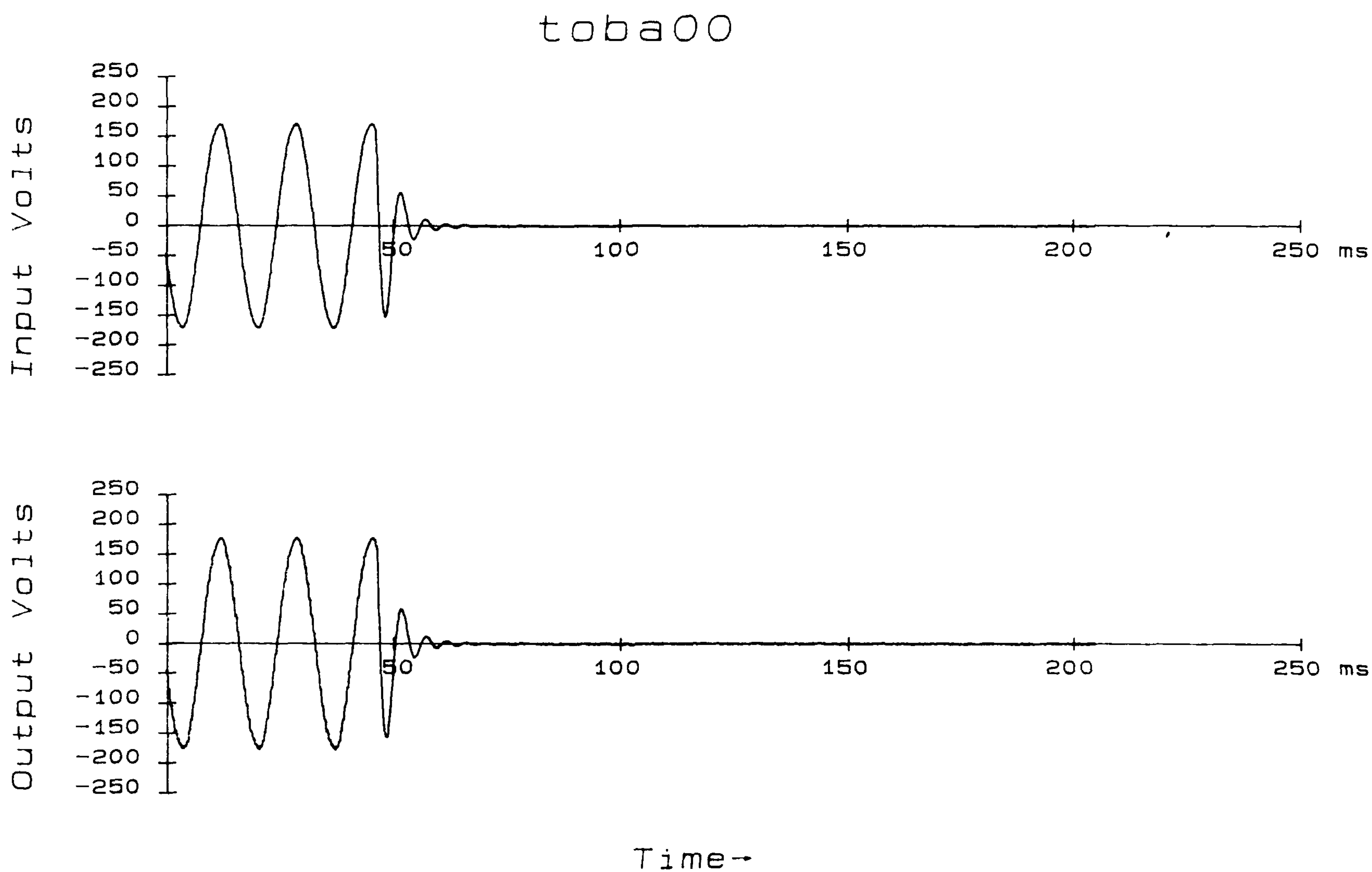
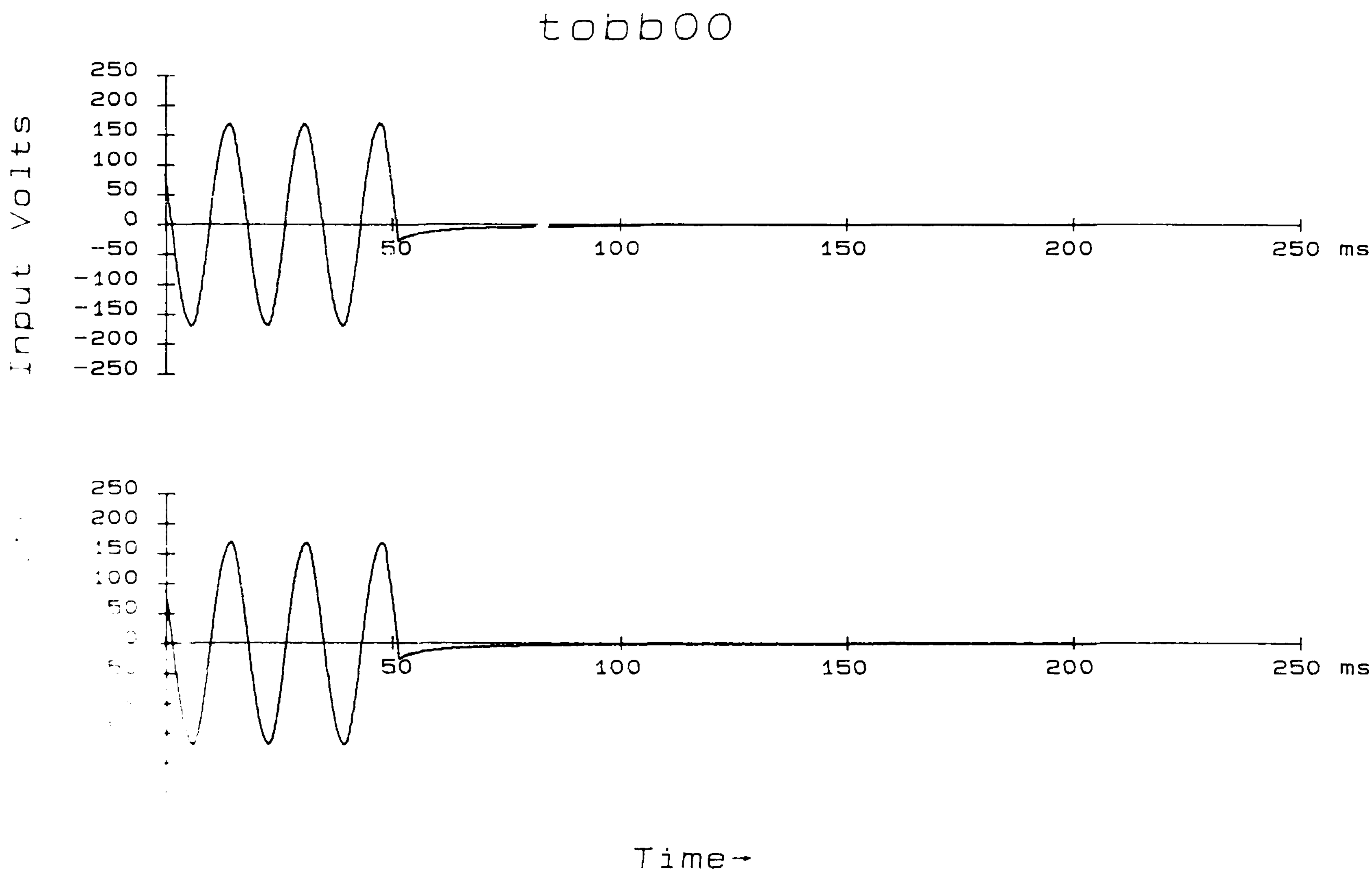


Figure 38. Shutdown test of a Topaz tap-switching conditioner with no load.



Shutdown test of a Topaz tap-switching conditioner with a 35 Ω load.

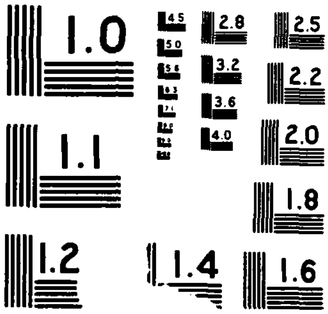
AD-A192 502 MITIGATION OF MAINS DISTURBANCES(U) PENNSYLVANIA STATE UNIV UNIVERSITY PARK R STANDLER ET AL NOV 87 AFWL-TR-86-80 F29601-85-K-0035

2/3

UNCLASSIFIED

F/G 10/2

NL


1.0
4.5
5.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.2
1.4
1.6

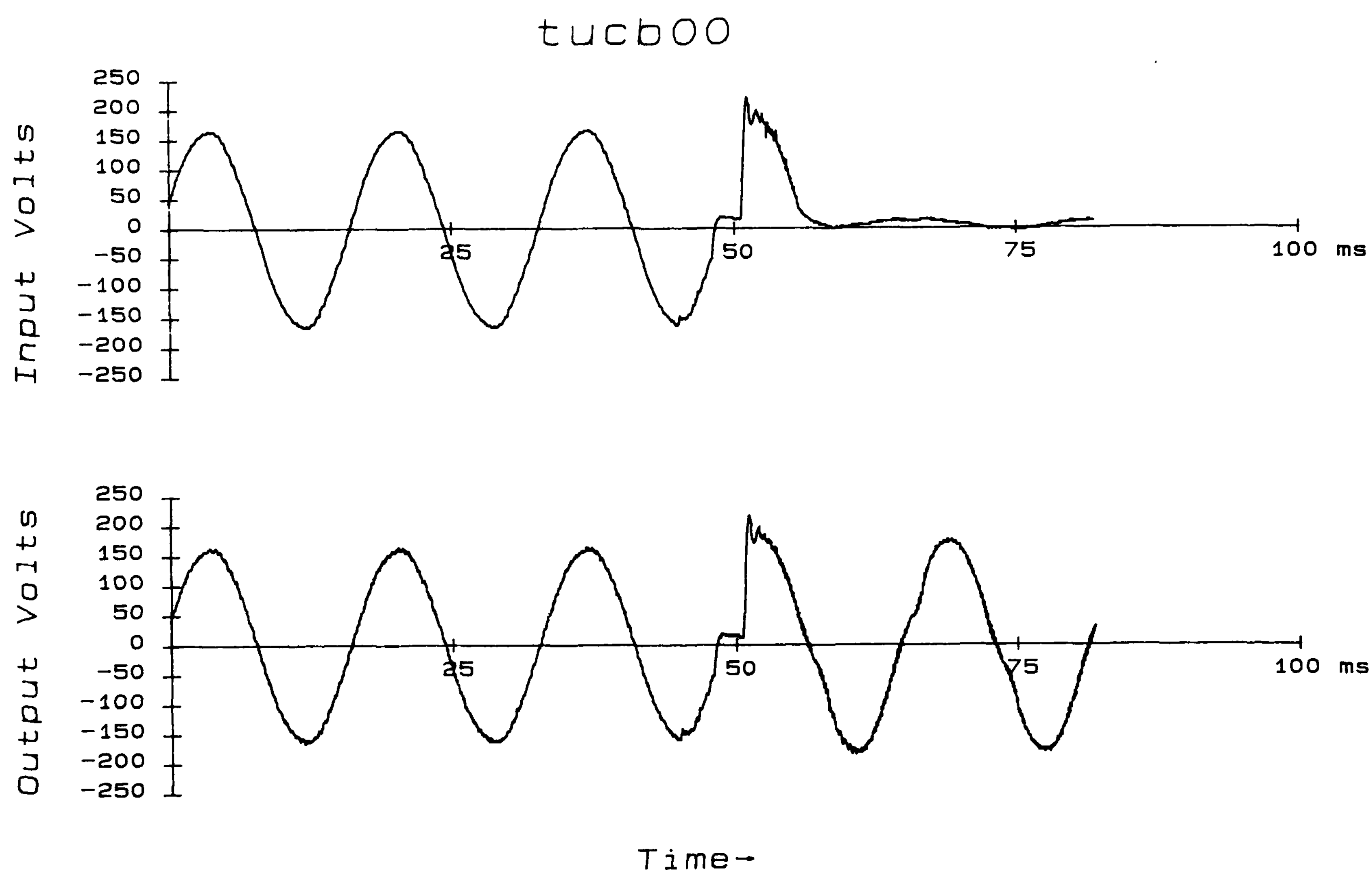


Figure 40. Shutdown test of a Topaz standby UPS with a 35 Ω load.

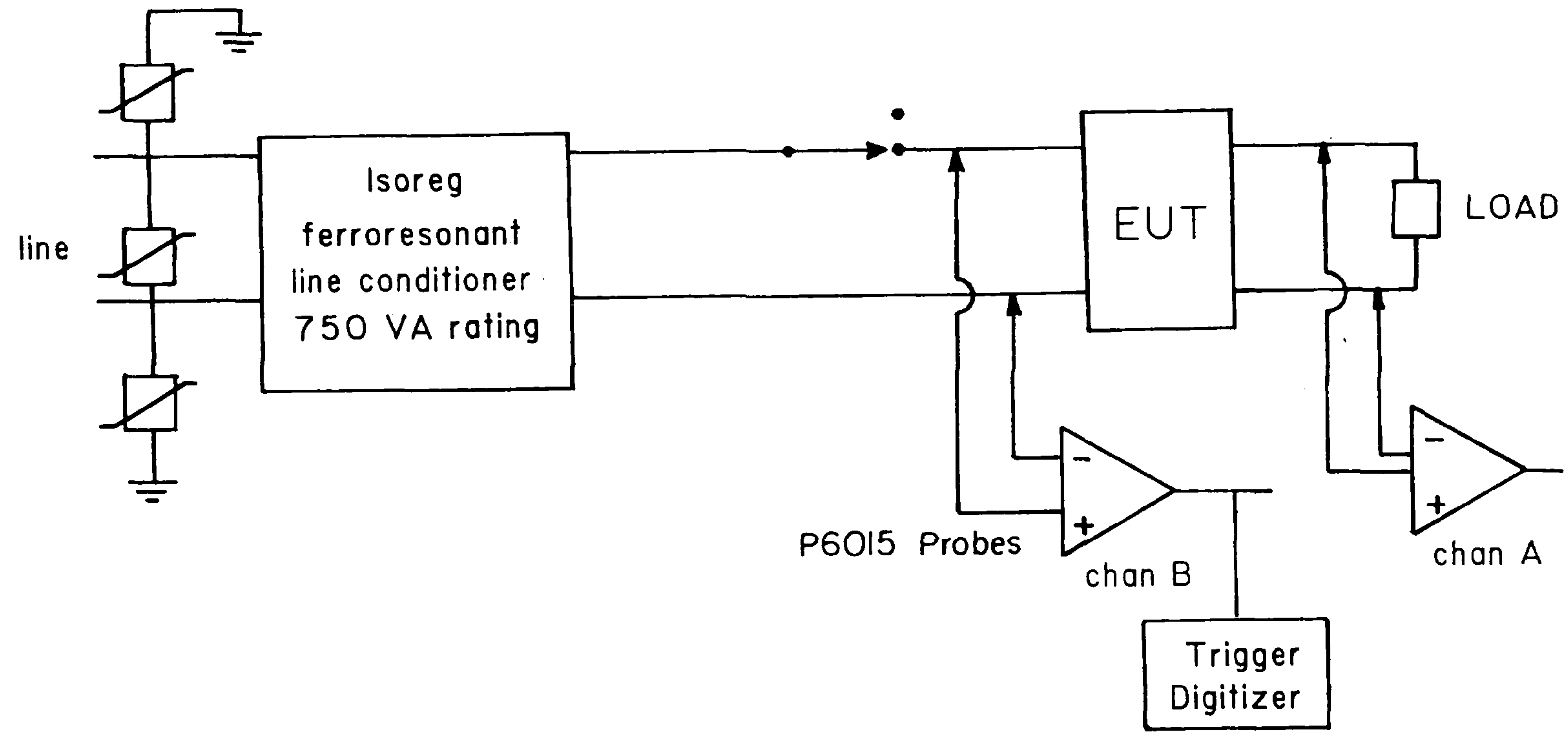


Figure 41. Isolated shutdown tests.

First, the Sola ferroresonant transformer was used as the EUT. When the power was disconnected from the EUT, a high-voltage transient appeared at the input of the EUT, as shown in Figs. 42 and 43 (files SOBB03 and SOBA03). In these figures the output voltage appears constant because the entire record of 2048 samples has a duration of only 0.1 ms. During this brief time the mains voltage is appreciably constant. After the input is disconnected, the output voltage continues unchanged because the ferroresonant output circuit continues to oscillate.

The peak input voltage in Fig. 42 (FILE SOBB03) is 631 V, about 3.7 times greater than the normal peak mains voltage.

Immediately before the largest peak in Fig. 43 (file SOBA03) is a series of 20 smaller peaks. Notice that these smaller peaks tend to get larger and more widely spaced in time as time progresses. We believe that the sudden decrease in voltage after each of these small peaks is due to an arc between the relay contacts. As the relay contacts moved farther apart, the voltage required for sparkover increased, which made the later peaks have a greater voltage.

The high-voltage transient that occurs when the input is disconnected also occurs with a tap-switching transformer, as shown in Fig. 44 (file TOBB01). The peak input voltage was 263 V.

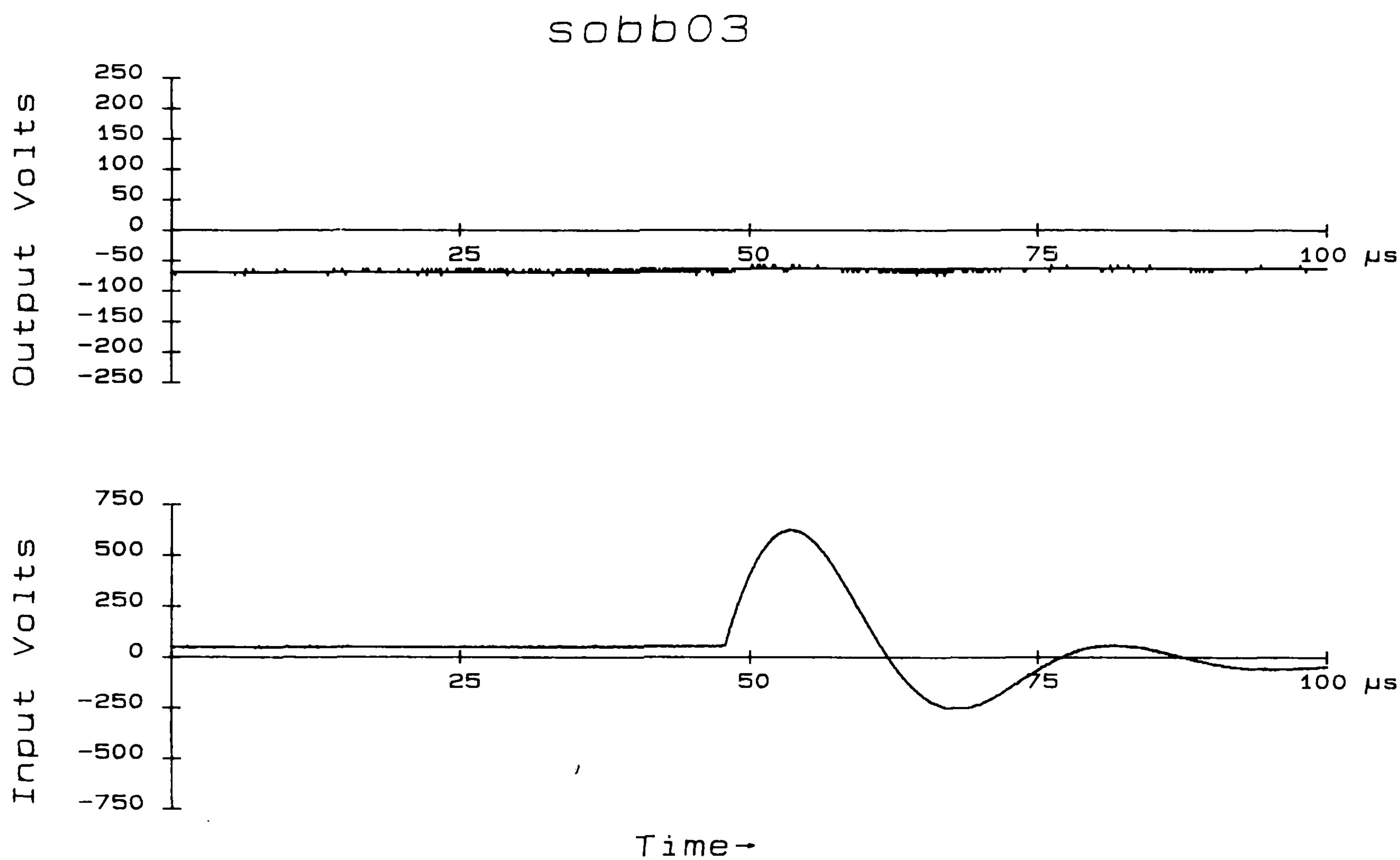


Figure 42. Shutdown test of a Sola ferroresonant conditioner with a 35 Ω load. The input of the conditioner was isolated.

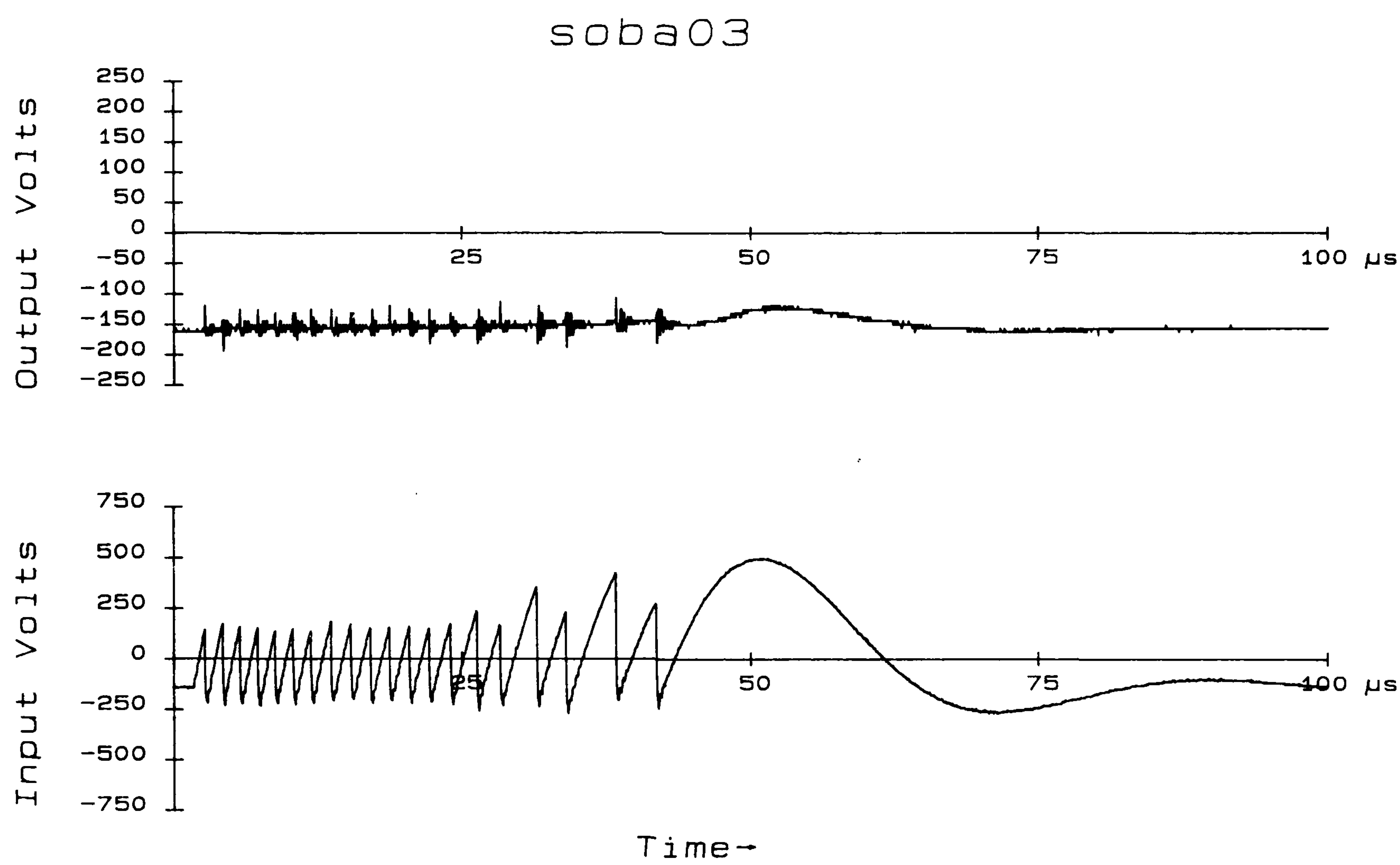


Figure 43. Shutdown test of a Sola ferroresonant conditioner with no load. The input of the conditioner was isolated.

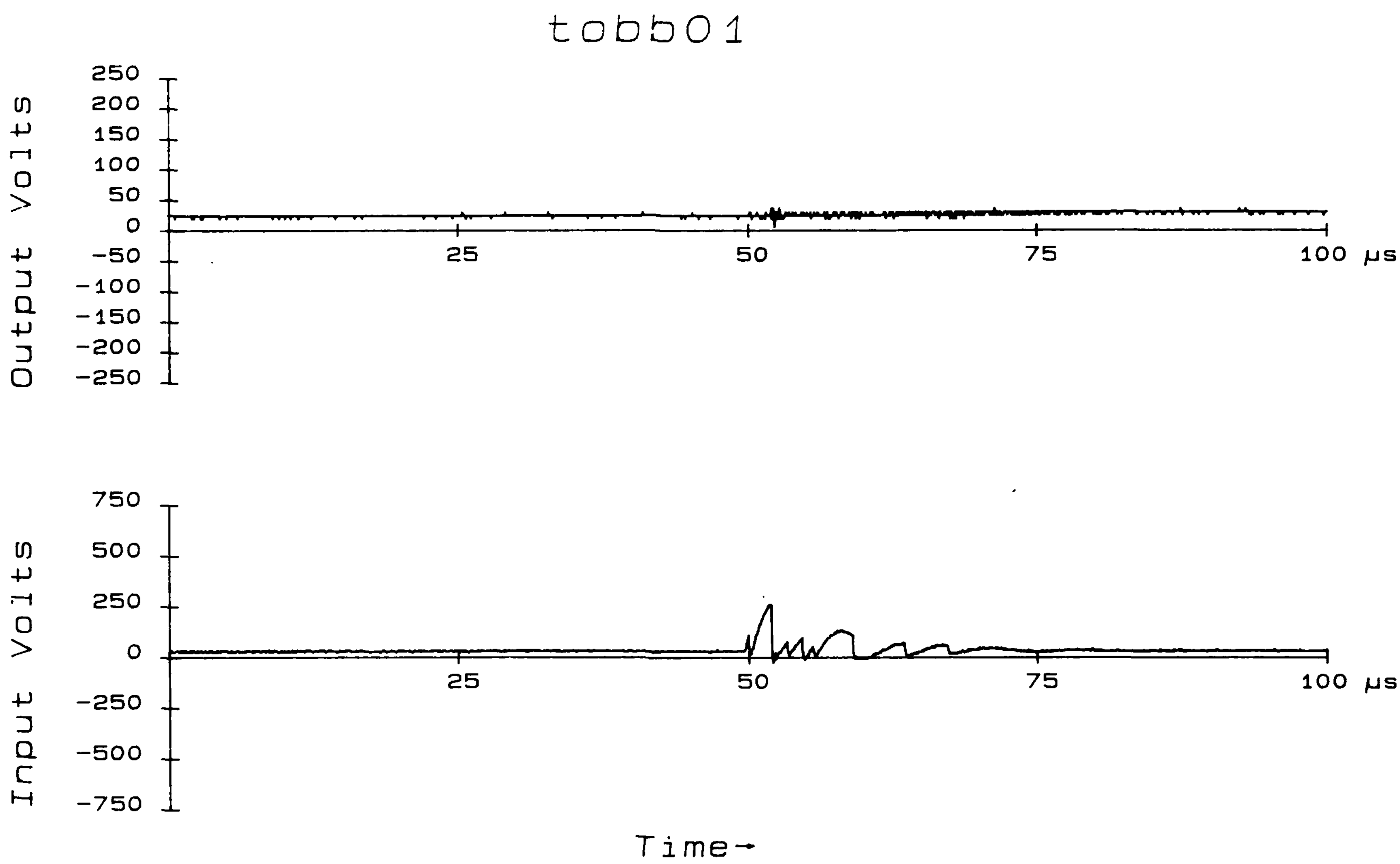


Figure 44. Shutdown test of a Topaz tap-switching conditioner with a 35 Ω load. The input of the conditioner was isolated.

SECTION 6

The previous section described various tests of line conditioners with simple loads: resistors, capacitors, motors. Such loads were chosen for laboratory experiments but are not typical of loads for practical applications of line conditioners. The most common load for line conditioners is a desktop computer and its peripherals (printer, cathode-ray tube monitor, modem, etc.). This section presents steady state and startup tests of line conditioners with a small computer as a load. The section concludes with tests of combinations of a standby uninterruptible power supply (UPS) and a line conditioner with a small computer as a load. The object is to simulate a blackout or loss of mains.

Two different computers were used as a load in these tests:

1. IBM PC/XT model 5160,
2. Hewlett Packard model 9836A.

Both machines are designed for use on single phase, 120 V rms, 60 Hz mains. The IBM power supply is rated as a 400 W load; the Hewlett Packard power supply is rated at 384 VA, 300 W. Both machines are rated by their manufacturer to operate from a range of steady-state voltages. IBM specified 90 to 137 V rms; Hewlett Packard specified 108 to 132 V rms. Additionally, the Hewlett Packard machine is specified to operate with "no loss of performance visible to user" if the mains voltage is between 84 and 108 V rms or between 132 and 156 V rms for a period of 500 ms or less.

To measure the minimum input voltage range for operation of the IBM PC/XT, we connected the machine to the output of a variable transformer in parallel with a Keithley model 179 true rms voltmeter. We began the test with the voltage at 120 V rms and slowly decreased it. At 102 V rms the image on the CRT monitor began to shrink. At 80 V rms theimage on the monitor began to get dimmer. The performance of the monitor was poor at 70 V rms, but the computer continued to operate. The computer quit operating at 67 V rms. We did not operate the disk drives during this test because we did not wish to risk damaging them.

The IBM PC/XT is specified for operation on nominal 50 Hz or 60 Hz mains. Hewlett Packard specified the 9836 computer for operation at mains frequencies between 48 and 66 Hz. Small frequency variations would not be expected to upset or damage either computer.

The Oneac device, as discussed in Section 4, does not provide any line or load voltage regulation. Literature from Oneac states that line regulation is "no longer needed because most computer-operated systems now use switching power supplies which are, themselves, inherently good line regulators." In the authors' opinion this is a reasonable view, provided that all of the power supplies in the computer system are switching power supplies. Peripheral devices with a small power consumption (e.g., a modem) usually contain a linear power supply. Linear power supplies are much more sensitive to brownouts than switching power supplies.

The steady-state voltage and current to the computers were measured with the circuit shown in Fig. 45. The P6015 voltage probes, 7A13 amplifiers, and digitizer were described in the section entitled "Dynamic Line Regulation Test Methods" of the previous section. The Tektronix CT-5, P6021, and 134 amplifier were described in the previous section in the section entitled "Dynamic Load Regulation Test Methods".

Figure 46 (file XXAH02) shows the steady-state current and voltage vs. time for an IBM PC/XT. Notice that the current flows in brief pulses with a duration of 1.85 ms, although a half cycle of 60 Hz mains voltage is 8.33 ms. The power supply in the computer is clearly a nonlinear load since the instantaneous voltage and current are not proportional. The peak current is 4.9 A. The apparent nonzero offset current between the peaks is an artifact of the AC coupled current transformer.

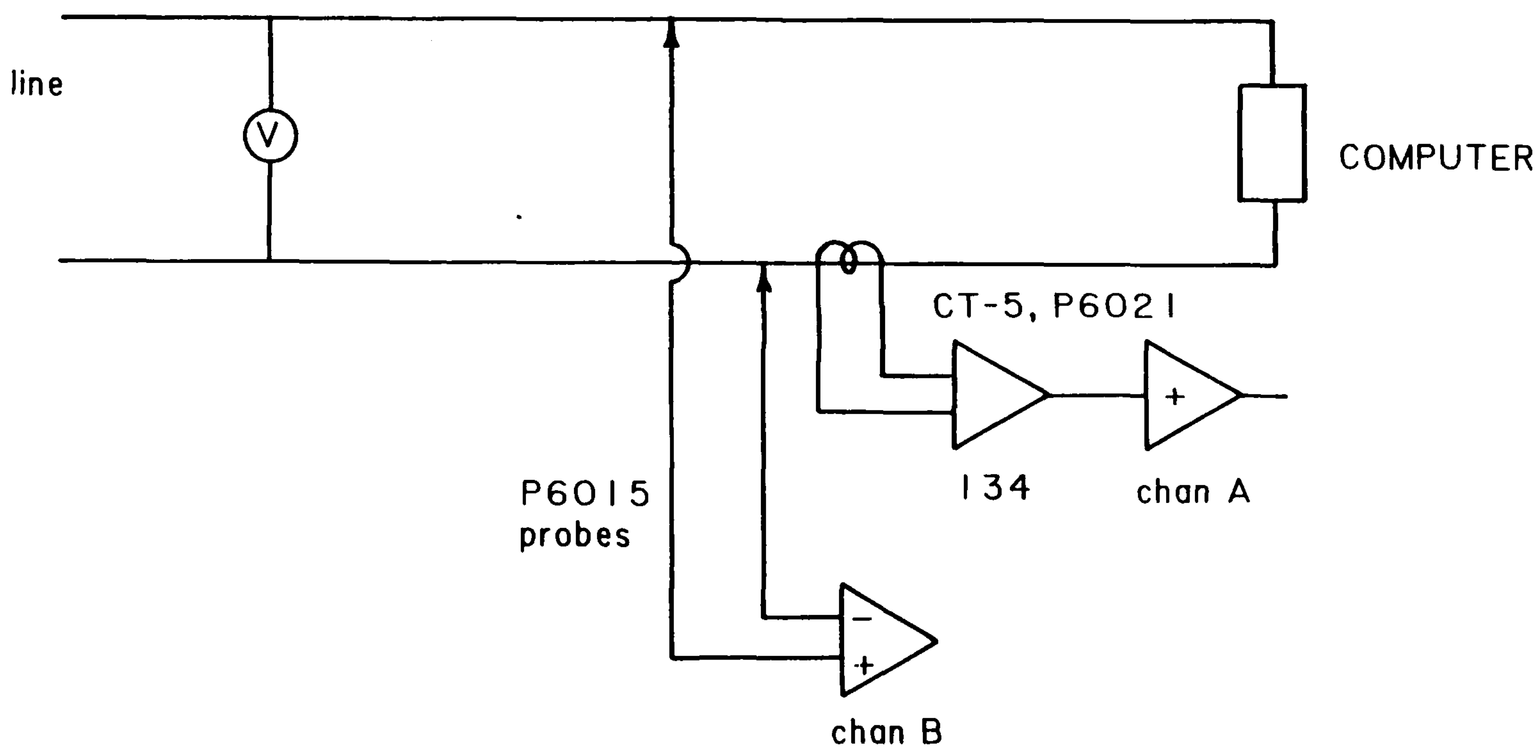


Figure 45. Steady state measurements of computer current.

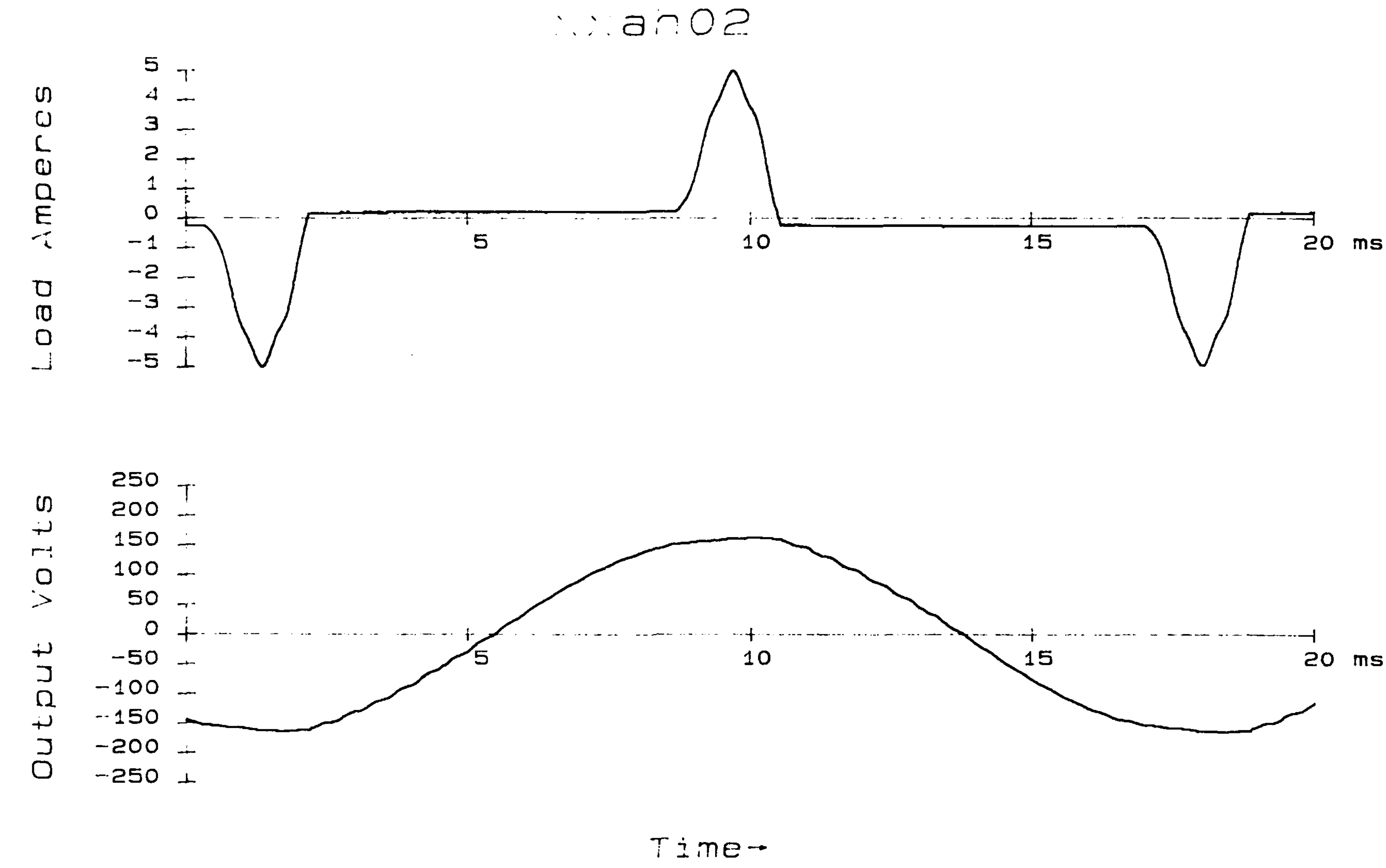


Figure 46. Steady-state mains current and voltage with an IBM PC/XT load.

Figure 47 (XXAJ01) shows the steady-state current and voltage vs. time for the Hewlett Packard 9836 computer. As with the IBM PC, the power supply is a nonlinear load. The current pulses have a duration of 2.9 ms and a peak value of 3.8 A.

COMPUTER STARTUP

When the computer is switched on, it draws a large amplitude surge of current. This was measured with the circuit shown in Fig. 48. The equipment under test (EUT) in Fig. 48 was absent when we measured the startup current of the computer. Later we connected a Sola ferroresonant line conditioner and the Topaz and Deltec tap-switching line conditioners, one at a time, as the EUT. The instrumentation was described in the previous section.

Figure 49 (file XXAH05) shows the mains current and voltage vs. time when the IBM PC/XT is switched on. The initial current surge has an amplitude of 33 A, which is 6.7 times the peak current during steady state. The discontinuities in voltage in Fig. 49 (file XXAH05) are due to bounce in the relay. They do not affect the current because they occur between current pulses.

We do not have a plot of the startup current for the 9836 computer due to an oversight.

The output impedance of a line conditioner, when combined with the computer's initial demand for large current, produces poor voltage regulation. Figure 50 (file SODH00) shows the output voltage of the Sola ferroresonant line conditioner when the IBM PC/XT computer is switched on. The line conditioner was operating in steady-state with no load prior to switching the computer on. Notice the distorted, low output voltage of the ferroresonant line conditioner between 47 and about 50 ms.

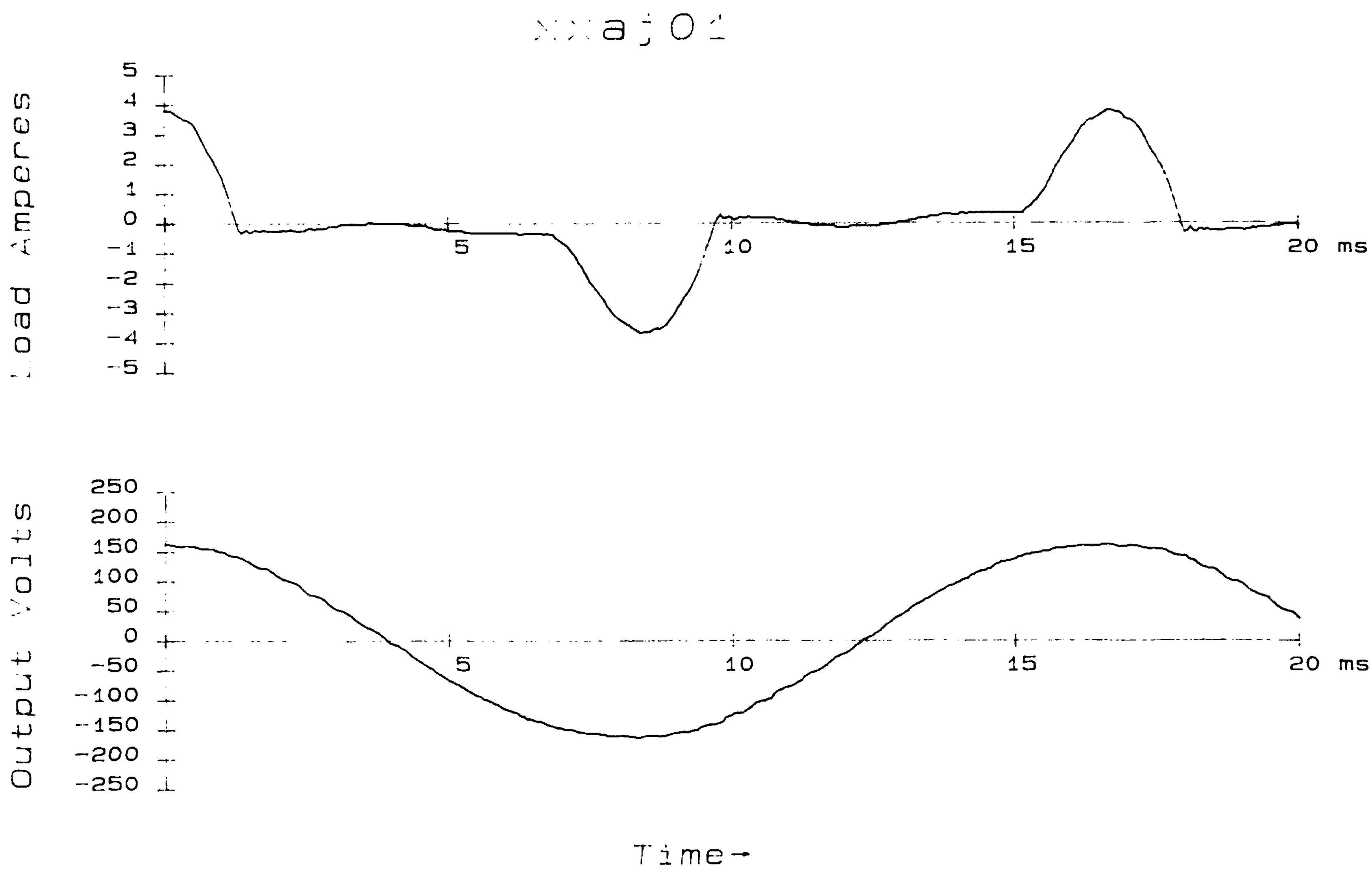


Figure 47. Steady-state mains current and voltage with an HP 9836 computer load.

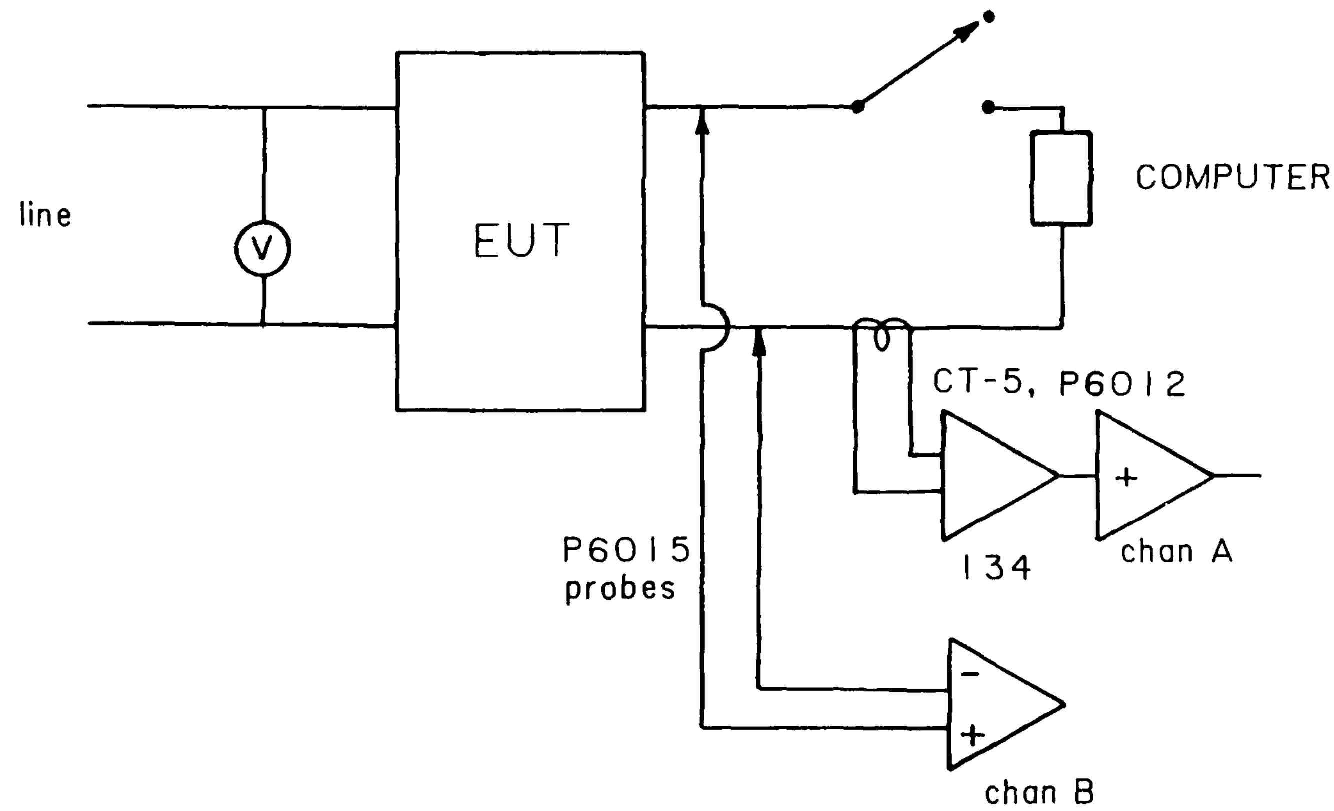


Figure 48. Computer startup tests.

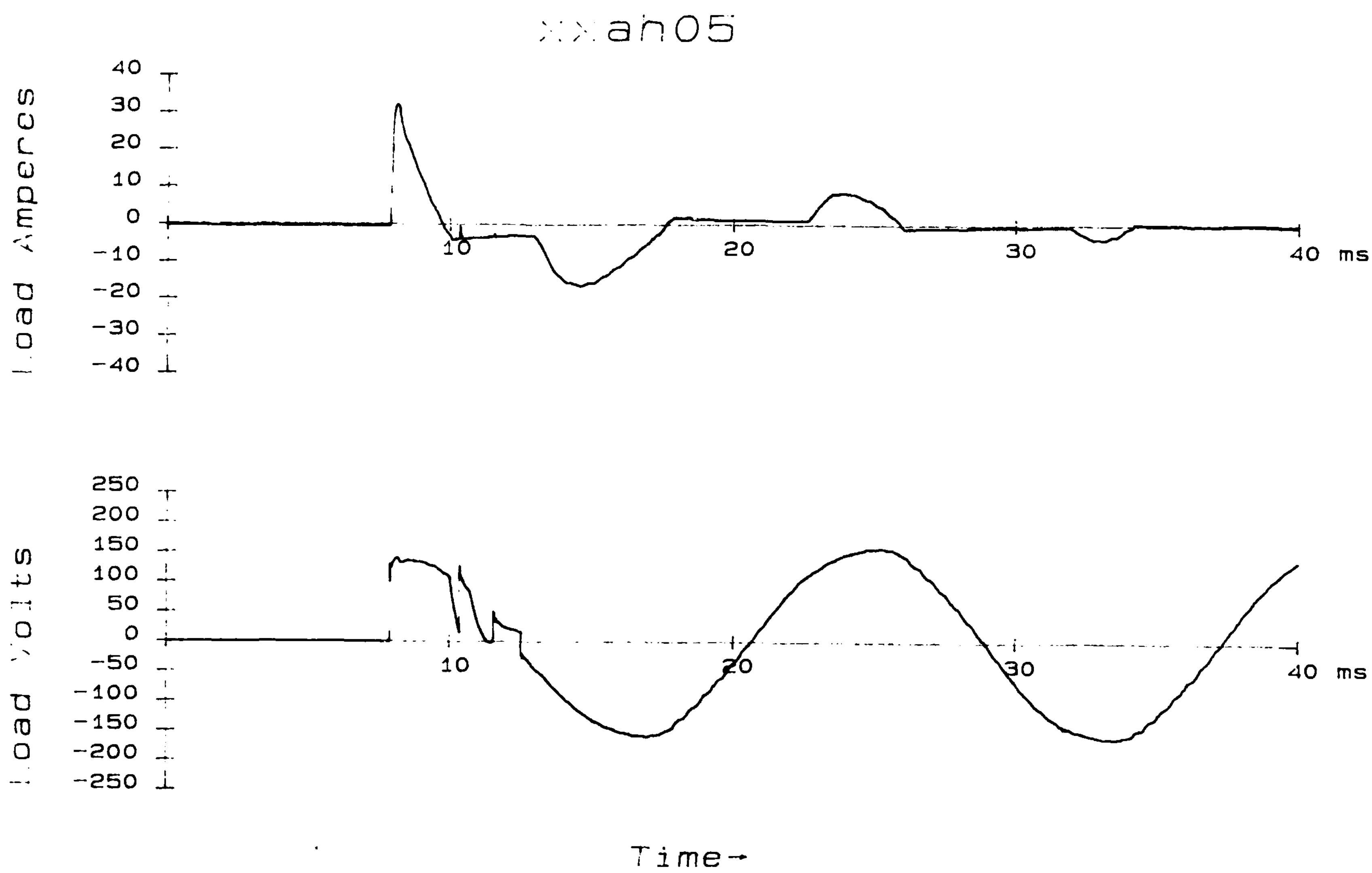


Figure 49. Startup test current and voltage with an IBM PC/XT without a line conditioner.

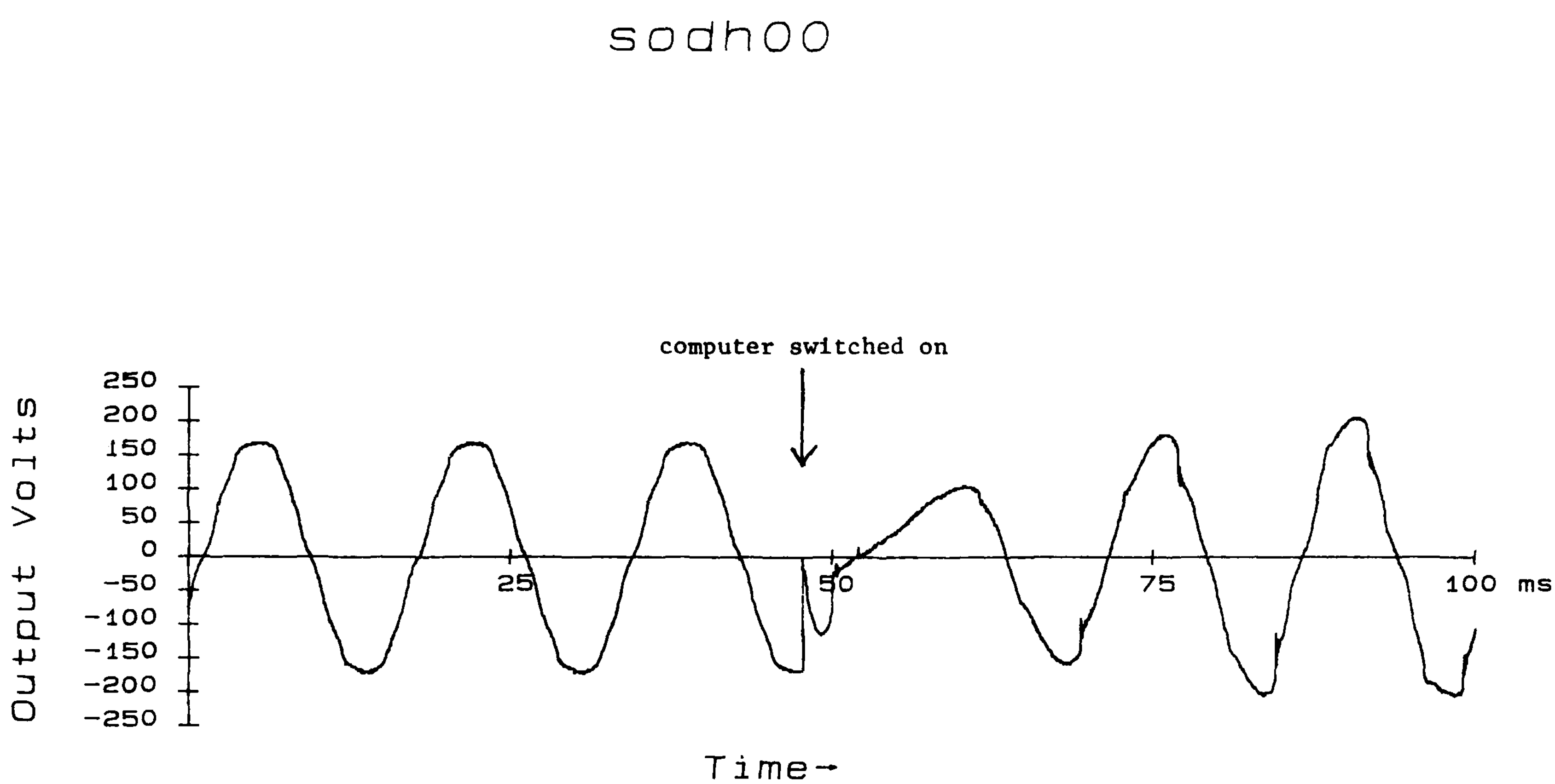


Figure 50. Computer startup test; output voltage of a Sola ferroresonant conditioner when an IBM PC/XT load was turned on.

During such demands for large current the ferroresonant transformer may emit an audible groan due to mechanical stress on the transformer core.

The output current record is not shown in Fig. 50 (file SODH00) and others that follow, due to artifacts in these records.

Figure 51 (file TODH01) shows the output voltage of the Topaz tap-switching line conditioner vs. time when the IBM PC/XT was switched on at 41.6 ms. The output voltage of the conditioner was distorted for three cycles after the computer was switched on. The distortion was particularly bad in the first cycle after switching. Other records that persist for longer durations than Fig. 51 (file TODH01) show that the output voltage of the Topaz tap-switching conditioner is sinusoidal for times beyond three cycles after the computer is switched on.

Figure 52 (file DEDH00) shows the output voltage of the Deltec tap-switching line conditioner vs. time when the IBM PC/XT was switched on at 33 ms. The behavior of the output voltage was similar to that for the Topaz tap-switching line conditioner.

Figure 53 (file SODJ00) shows the output current and voltage of the Sola ferroresonant conditioner vs. time when the Hewlett Packard 9836 computer was switched on. The initial current surge of 16 A and the output impedance of the ferroresonant transformer caused the instantaneous output voltage to decrease by 114 V. The output voltage was then distorted for the first 1.5 cycles after the computer was switched on. Four cycles after the computer was switched on, the peak current was 6 A, about 160% of the steady-state value.

Figure 54 (file TODJ01) shows the output current and voltage of the Topaz tap-switching line conditioner vs. time when the Hewlett Packard 9836 computer was switched on. The tap-switching output voltage reached steady-state in less than one cycle after the computer was switched on, somewhat faster than the ferroresonant transformer.

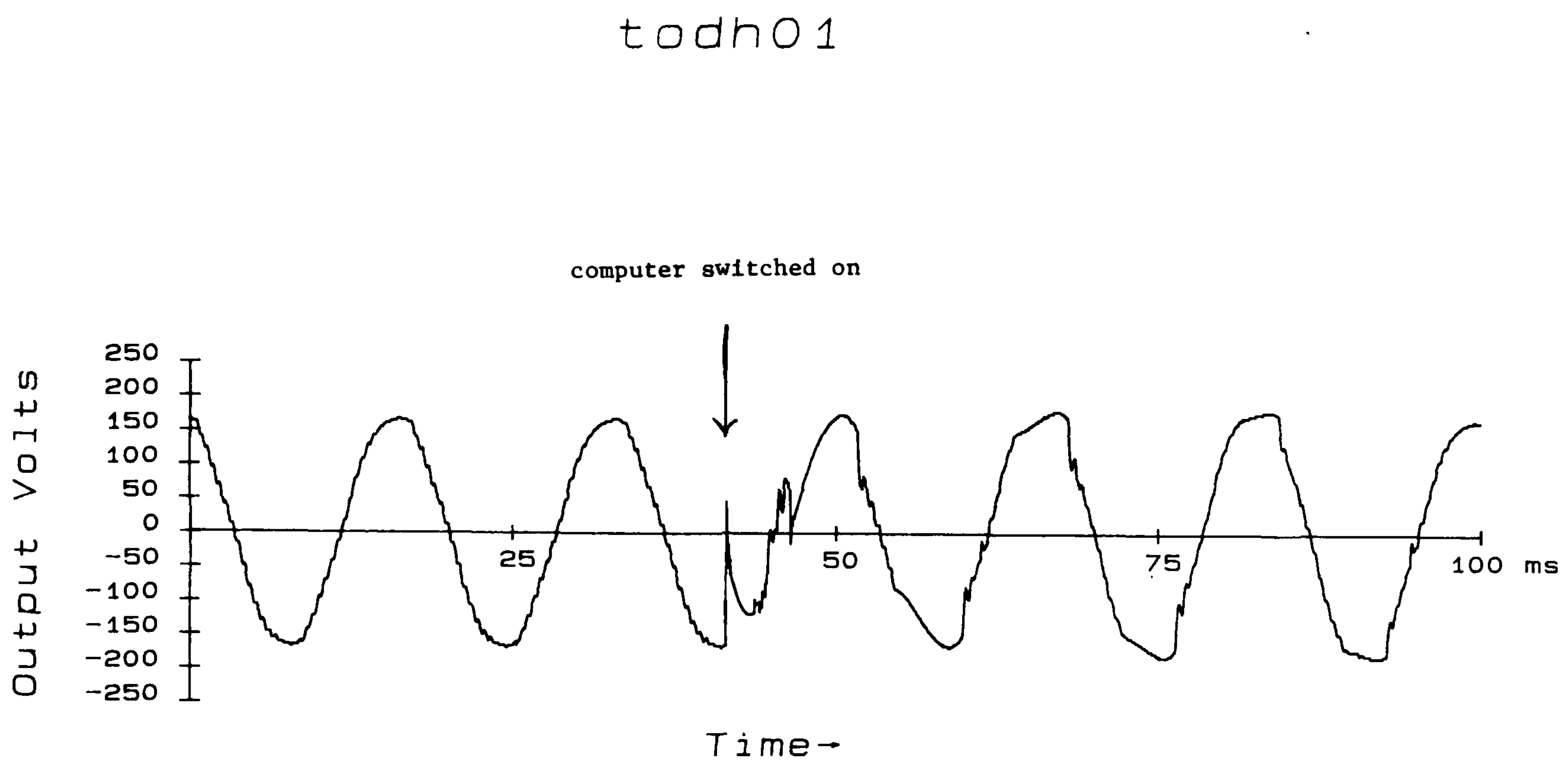


Figure 51. Computer startup test; output voltage of a Topaz tap-switching conditioner when an IBM PC/XT load was turned on.

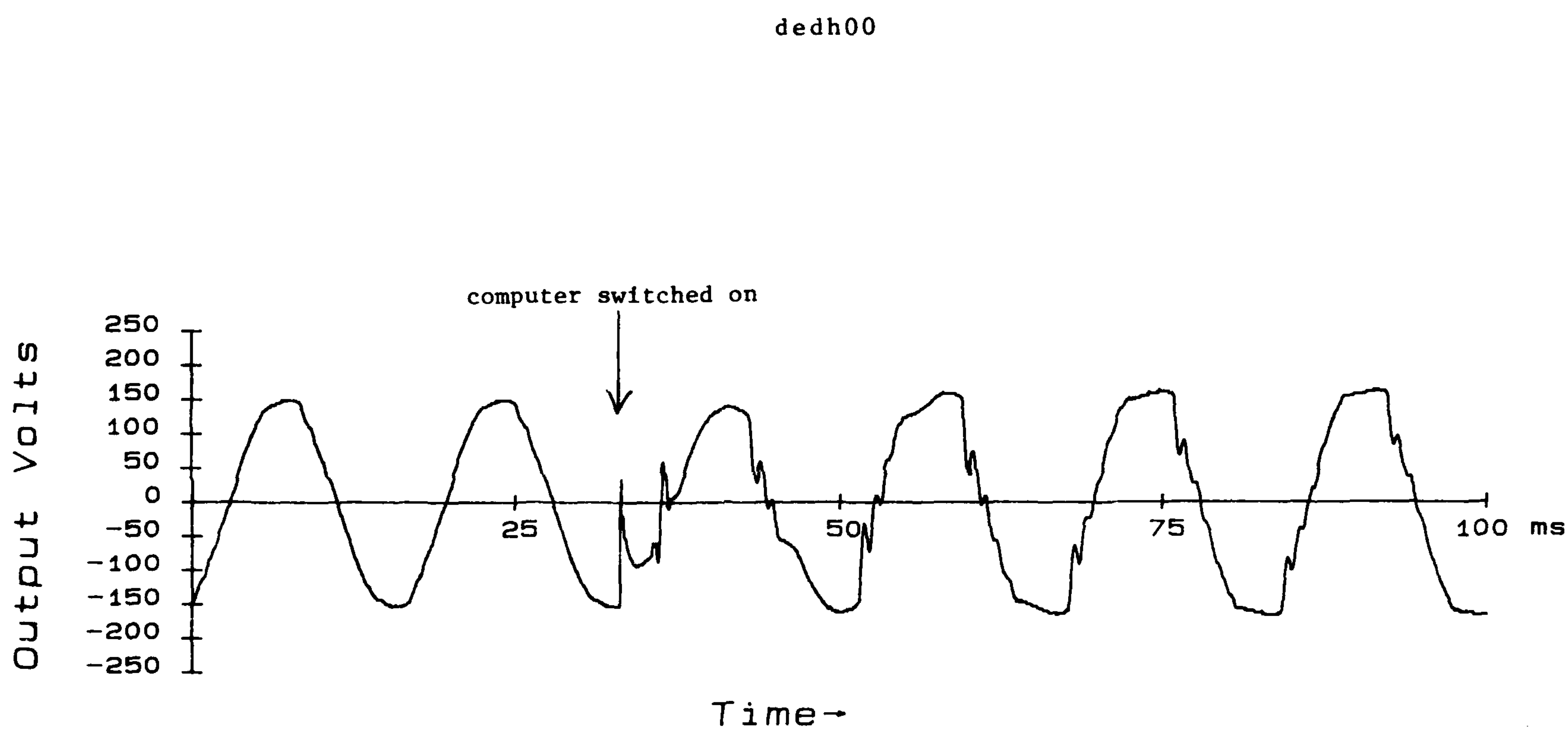


Figure 52. Computer startup test; output voltage of a Deltec tap-switching conditioner when an IBM PC/XT load was switched on.

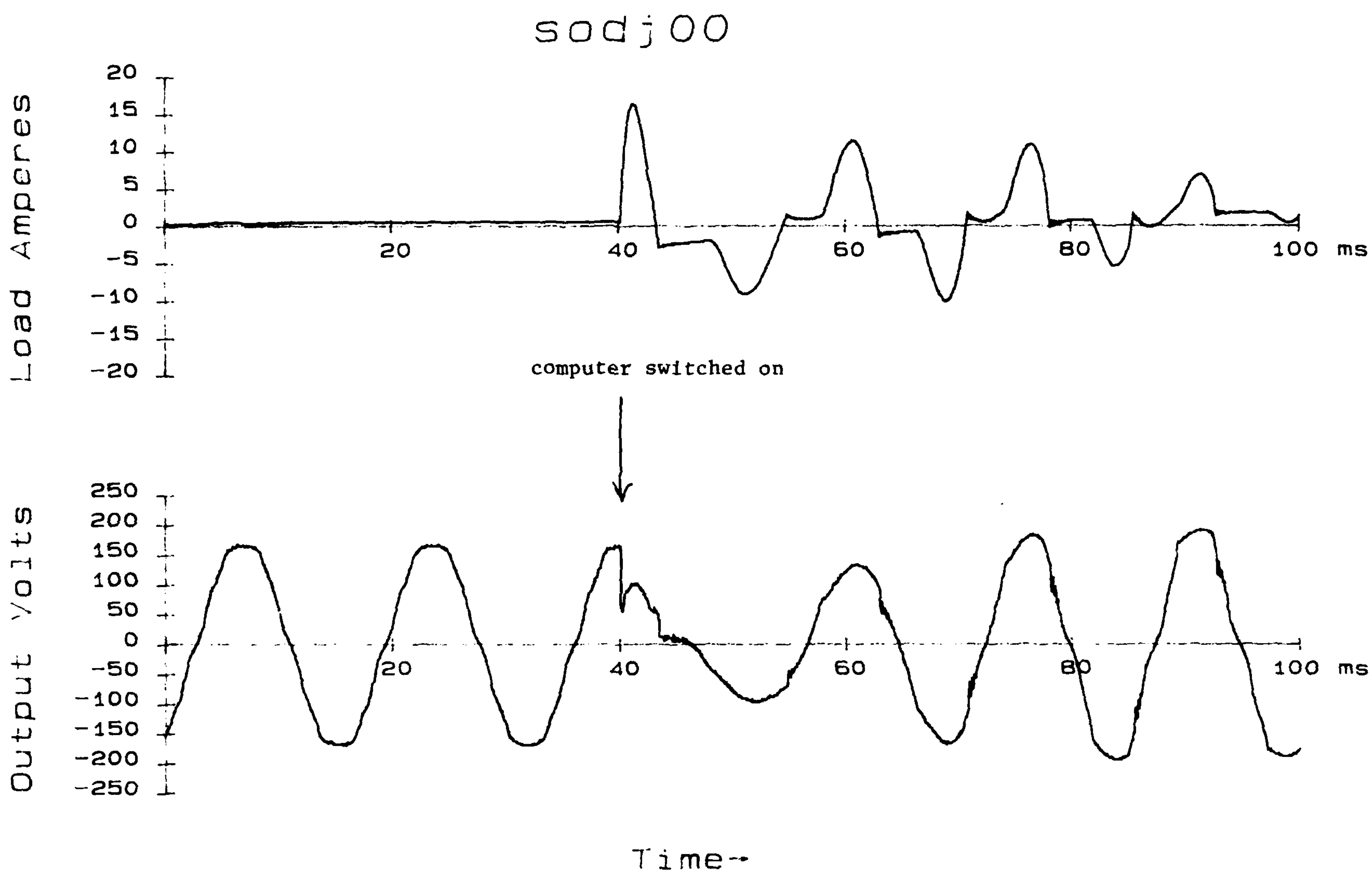


Figure 53. Computer startup test; output voltage of a Sola ferroresonant conditioner when an HP 9836 computer load was turned on.

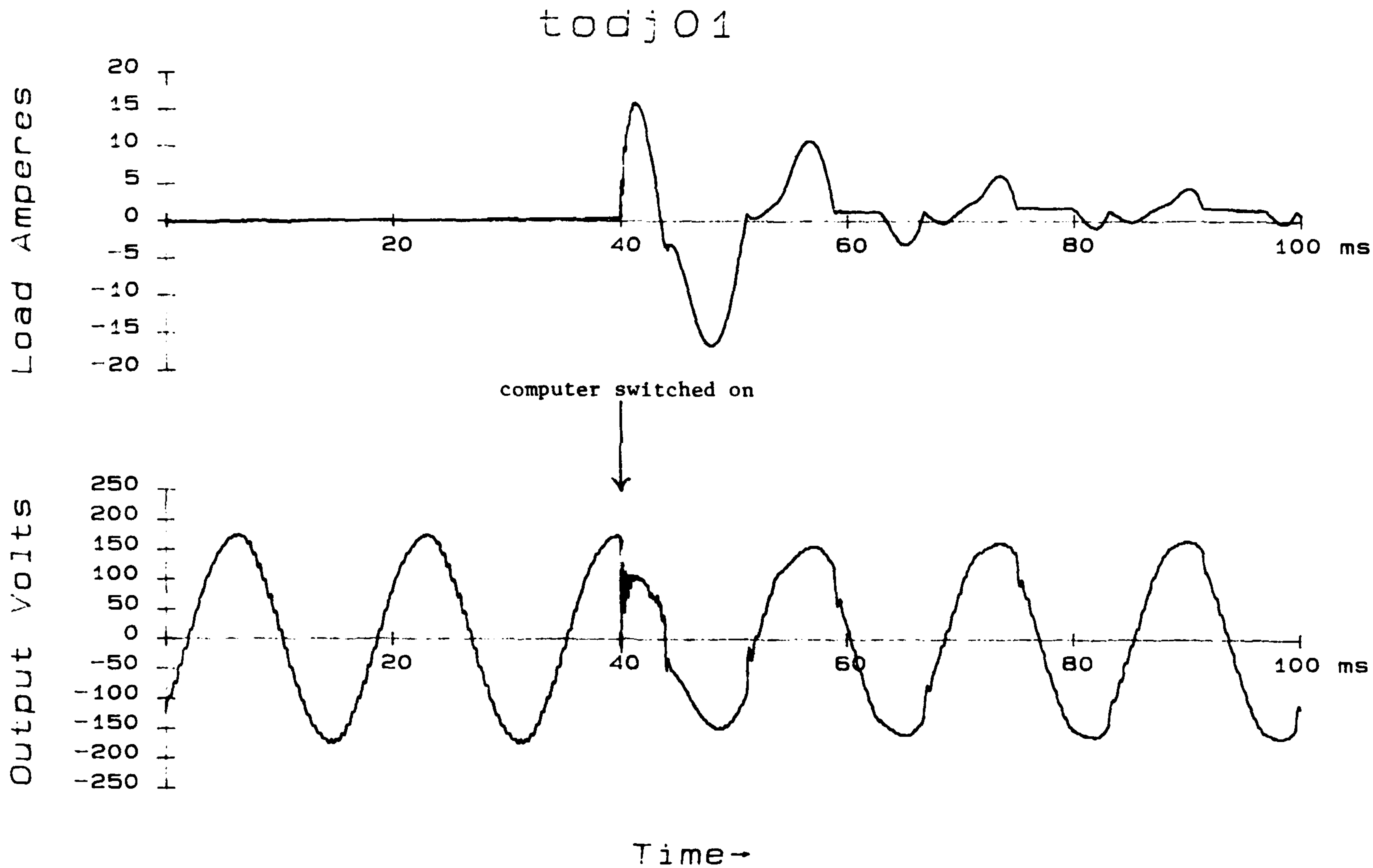


Figure 54. Computer startup test; output current and voltage of a Topaz tap-switching conditioner when an HP 9836 computer load was turned on.

Switching a computer on when it is connected to a line conditioner definitely stresses the line conditioner. One of us (RS) has accumulated a total of four and a half years of experience with two desktop computers (a Hewlett Packard 9836 and a North Star Advantage), each of which was connected to its own ferroresonant line conditioner. Although the line conditioner emits an audible groan every time a computer is switched on, the computers and line conditioners have been trouble free. The computers have never failed to boot properly.

UPS AND DESKTOP COMPUTERS

Line conditioners cannot save a computer from crashing if the mains are interrupted for more than a few cycles. To prevent upset of a computer system during a long flicker or a blackout, a UPS is required. A standby UPS was tested with a computer as a load using the circuit shown in Fig. 55. The instrumentation is discussed in the previous section.

Figure 56 (file TUCH00) shows the input and output voltage of the Topaz standby UPS connected to an IBM PC/XT. The mains were switched off sometime between 30 and 37 ms. The inverter in the UPS then turned on and supplied power to the computer. Apparently the inverter also supplied power to the input side, which is an open circuit, between 37 and 45 ms. The inverter's output voltage is a sinusoid when a 35 Ω resistor is used for a load (see Fig. 40, file TUCB00). The large peak current drawn by the computer and the output impedance of the UPS caused the peak output voltage of the UPS to be flattened. While the output voltage of the UPS is distorted, the IBM PC/XT operated flawlessly from this UPS.

Figure 57 (file TUCJ02) shows the input and output voltage of the Topaz standby UPS when connected to the Hewlett Packard 9836 computer. The mains were switched off sometime between 18 and 28 ms. The interpretation of this plot is similar to that of Fig. 56 (file

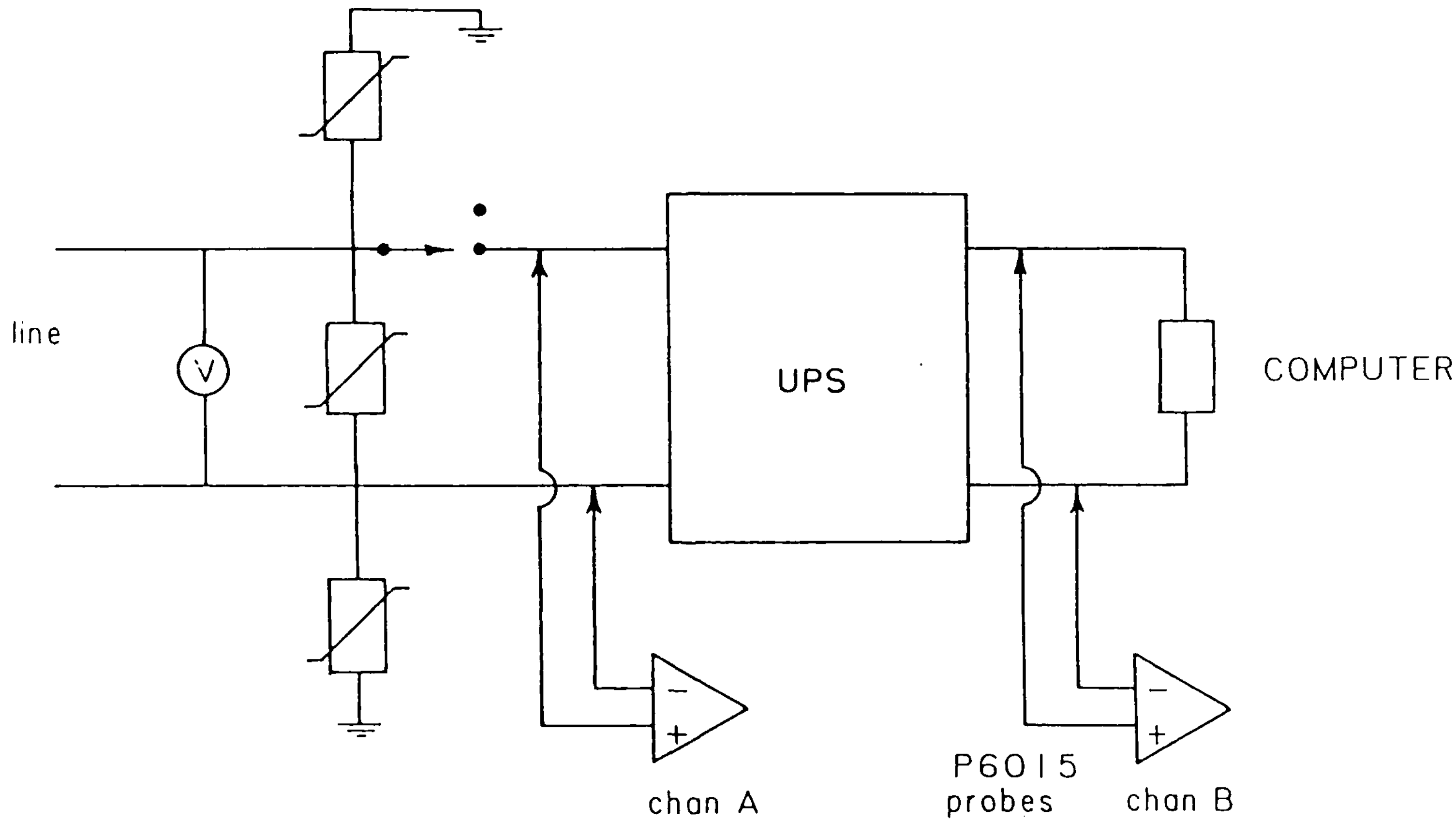


Figure 55. Tests of computer load with standby UPS.

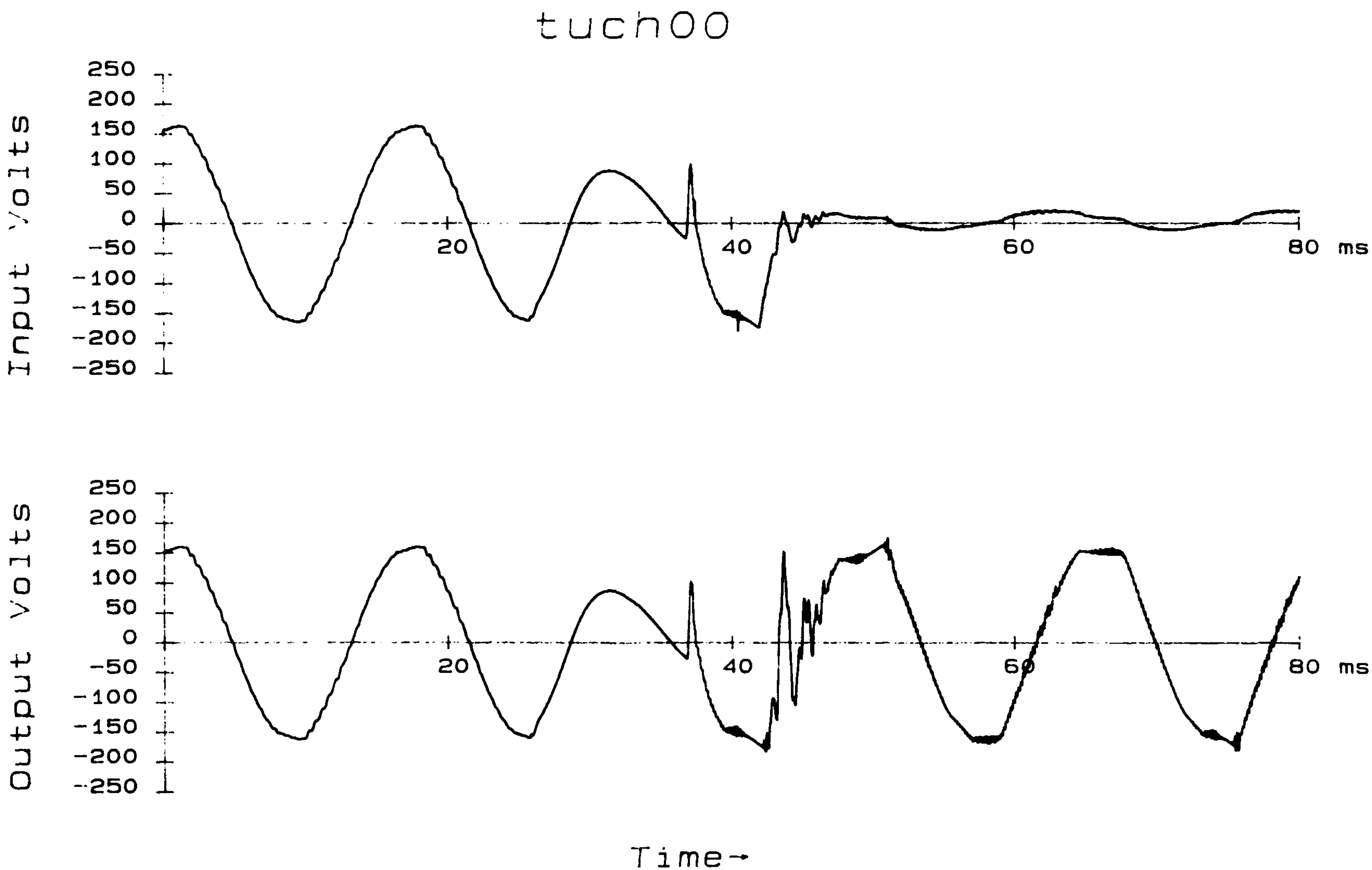


Figure 56. Computer shutdown test; input and output voltage of a standby UPS with an IBM PC/XT load when the mains were switched off.

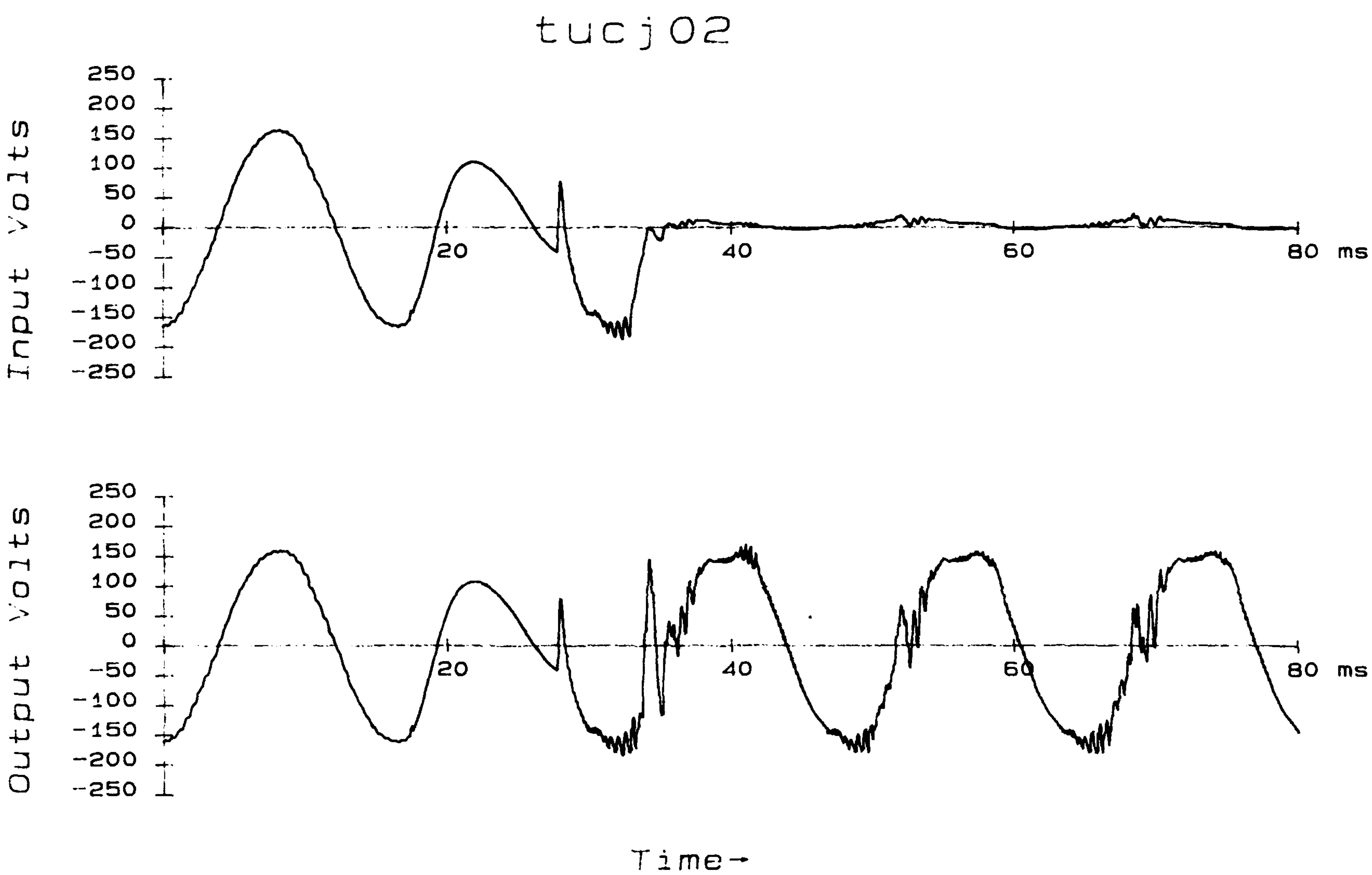


Figure 57. Computer and shutdown test; input and output voltage of a standby UPS with an HP 9836 computer load when the mains were switched off.

TUCB00) for the IBM PC/XT computer. The output voltage of the UPS was much noisier when the 9836 computer was connected than when the PC/XT computer was connected. This noise is not inherent in the 9836 since it does not appear in Fig. 47 (file XXAJ01).

UPS WITH FERRORESONANT CONDITIONER UPSTREAM

The combination of MOVs and a ferroresonant line conditioner upstream from a standby UPS, as shown in Fig. 58, provides comprehensive protection from disturbances on the mains to the computer. The varistors attenuate transient overvoltages and the ferroresonant line conditioner provides both attenuation of common- and differential-mode noise and regulation of the rms voltage. The UPS provides power during an outage or during a long duration flicker that depletes the energy stored in the conditioner's resonant circuit.

Placing the ferroresonant line conditioner upstream from the standby UPS has the following advantages:

1. The conditioner boosts the mains voltage during brownouts, thus avoiding discharging the batteries in UPS.

2. The conditioner boosts the mains voltage during sags, thus avoiding wear of the inverter and switching circuits inside the UPS.

3. The UPS does not need to supply the large input current surge when a ferroresonant conditioner downstream from the UPS is switched on. (This surge can trip the circuit breaker inside the UPS, even when no load is connected to the conditioner.)

Despite the authors' preference for this circuit, the line conditioner cannot remove noise created by the UPS (e.g., Fig. 57, file TUCJ02).

Figure 59 (file TUCH10) shows the input voltage of the ferroresonant conditioner and the output voltage of the UPS vs. time

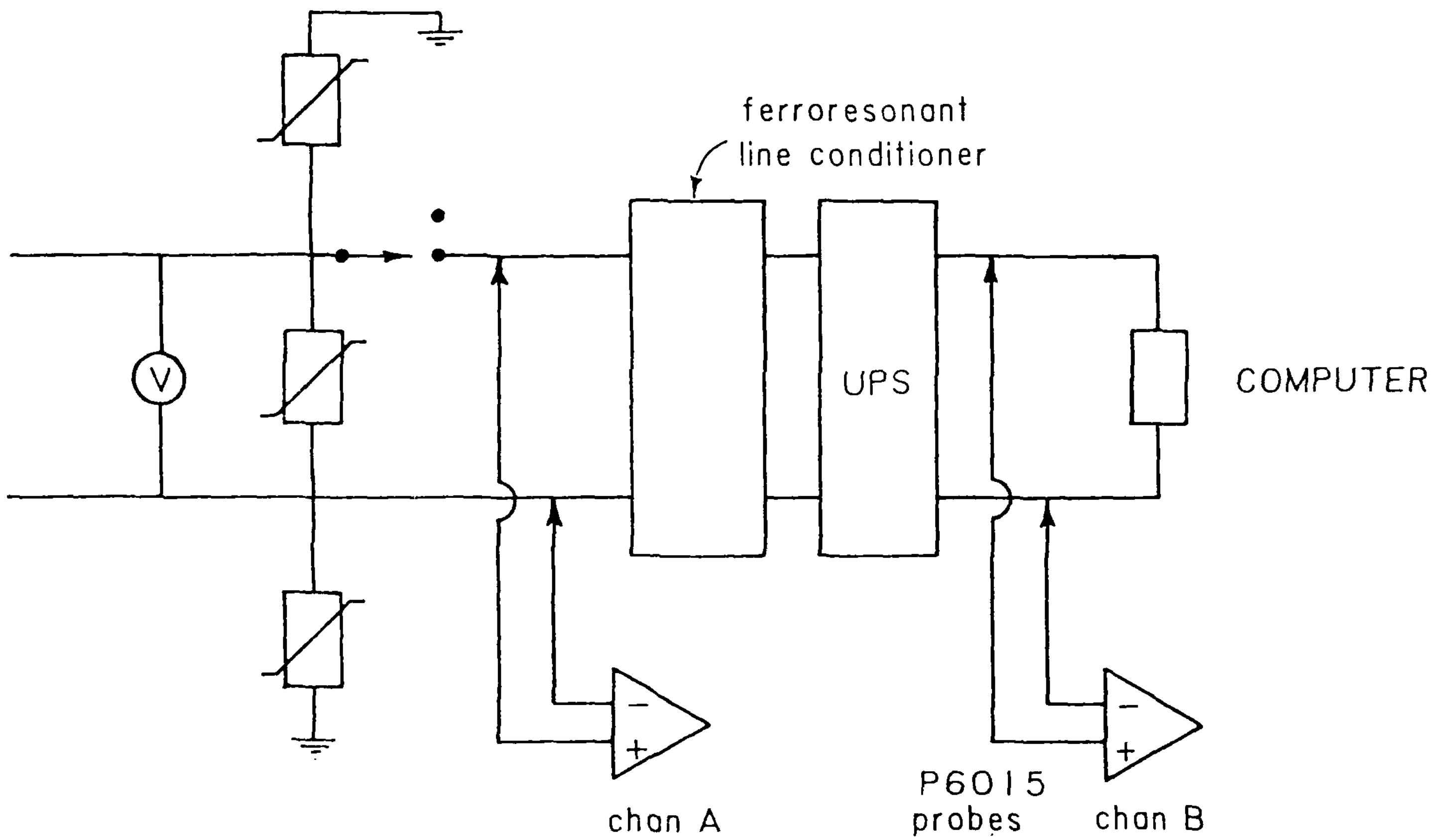


Figure 58. Tests with ferroresonant conditioner upstream from standby UPS.

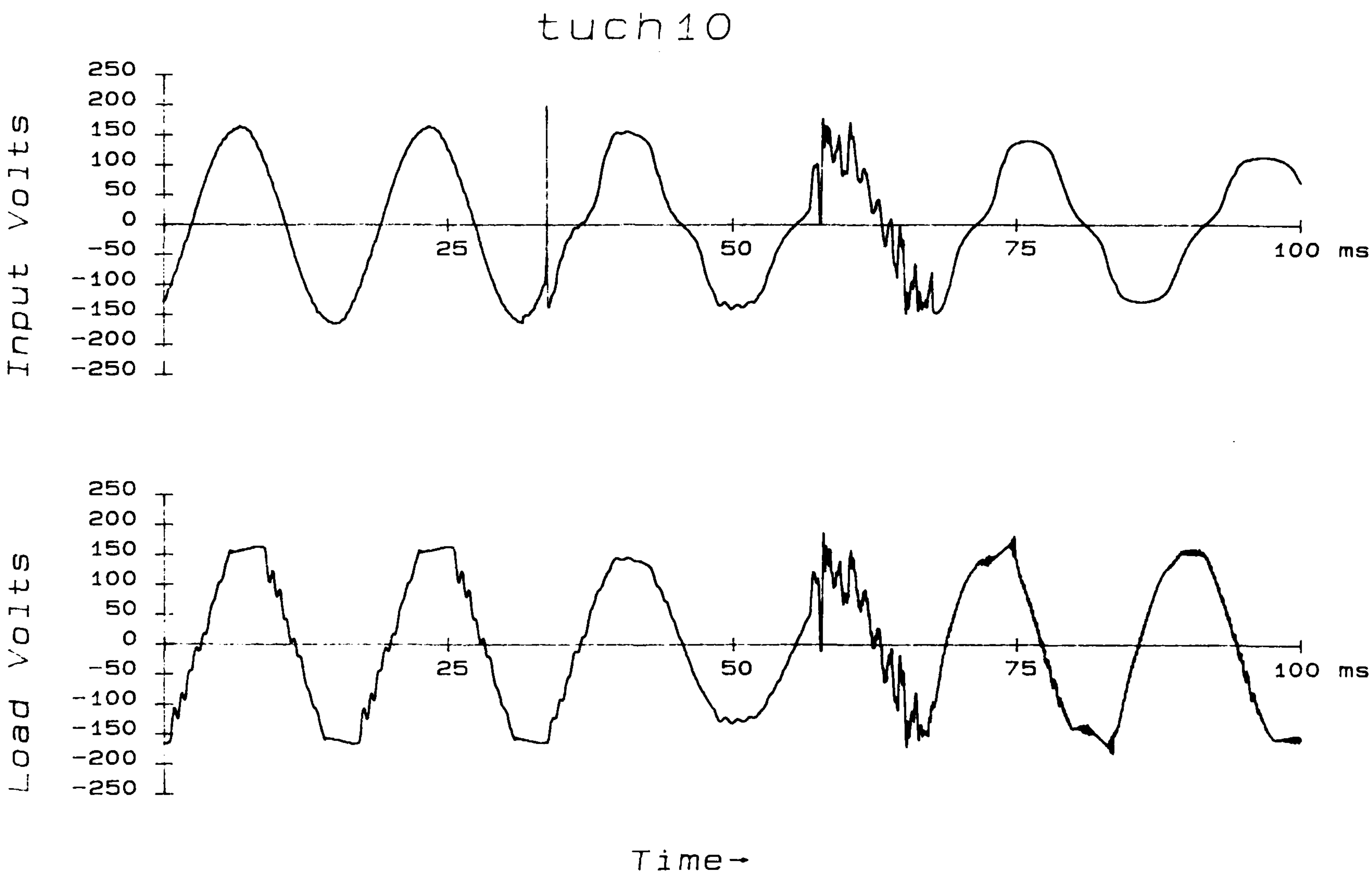


Figure 59. Sola ferroresonant conditioner upstream from standby UPS with an IBM PC/XT load: input voltage of conditioner and output voltage of UPS when the mains were switched off.

when the IBM PC/XT is connected as a load as shown in Fig. 58. The mains were disconnected at 33.6 ms. The input voltage of the ferroresonant line conditioner exceeded 200 V (full scale on the digitizer with the scale used during this experiment). This kind of transient is shown in greater detail in Fig. 42 (file SOBB03). The input voltage of the ferroresonant line conditioner then exhibits the behavior shown in Fig. 37 (file SOBG00).

The load voltage was distorted before the mains were disconnected because of the ferroresonant transformer's output impedance and the large peak current drawn by the computer. After the mains were disconnected, the distortion of the load voltage was due to the output impedance of the UPS and the large peak current drawn by the computer. Despite the distortion the computer operated without problems.

Figure 60 (file TUCJ03) shows the behavior of the Hewlett Packard 9836 computer in the circuit of Fig. 58. The mains were disconnected at 27.7 ms in Fig. 60. The features and interpretation of Fig. 60 are the same as for Fig. 59 (file TUCH10), which was explained above. The noise on the load voltage after the inverter in the UPS is connected to the load is similar to Fig. 57 (file TUCJ02).

UPS WITH TAP-SWITCHING CONDITIONER UPSTREAM

The Topaz tap-switching line conditioner was substituted for the ferroresonant line conditioner, as shown in Fig. 61, and the experiments were continued.

Figure 62 (file TUCH07) shows the behavior of the system in Fig. 61when an IBM PC/XT was used as a load. The mains were disconnected sometime between 18 and 28.5 ms. The input voltage of the line conditioner decays in the same way as shown in Fig. 38 (file TOBA00). The UPS operates the load after 40 ms. The load voltage reached 190 V at 28.5 ms when the load was probably switched to the inverter.

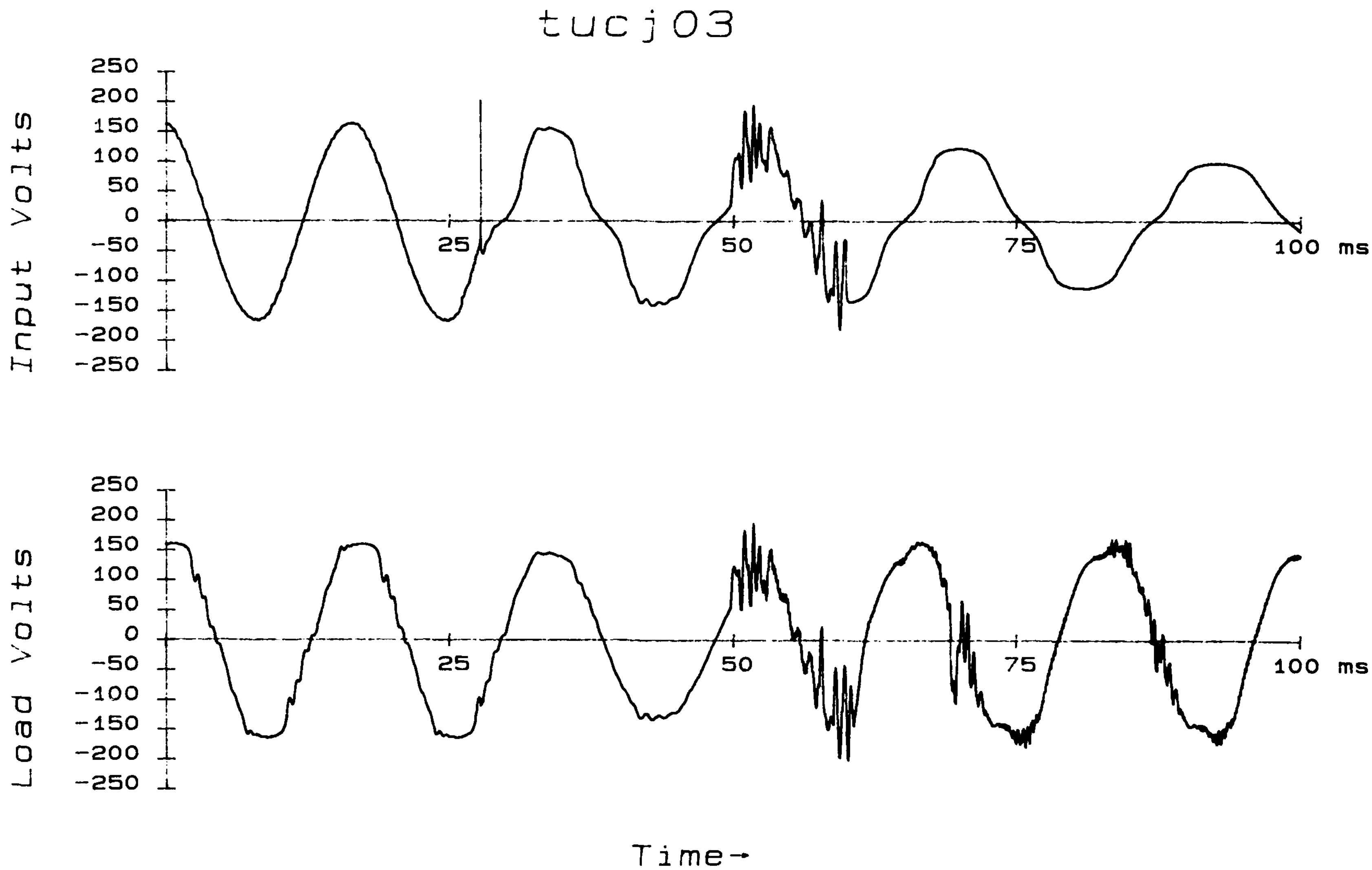


Figure 60. Sola ferroresonant conditioner upstream from standby UPS with an HP 9836 computer load; input voltage of conditioner and output voltage of UPS when the mains were switched off.

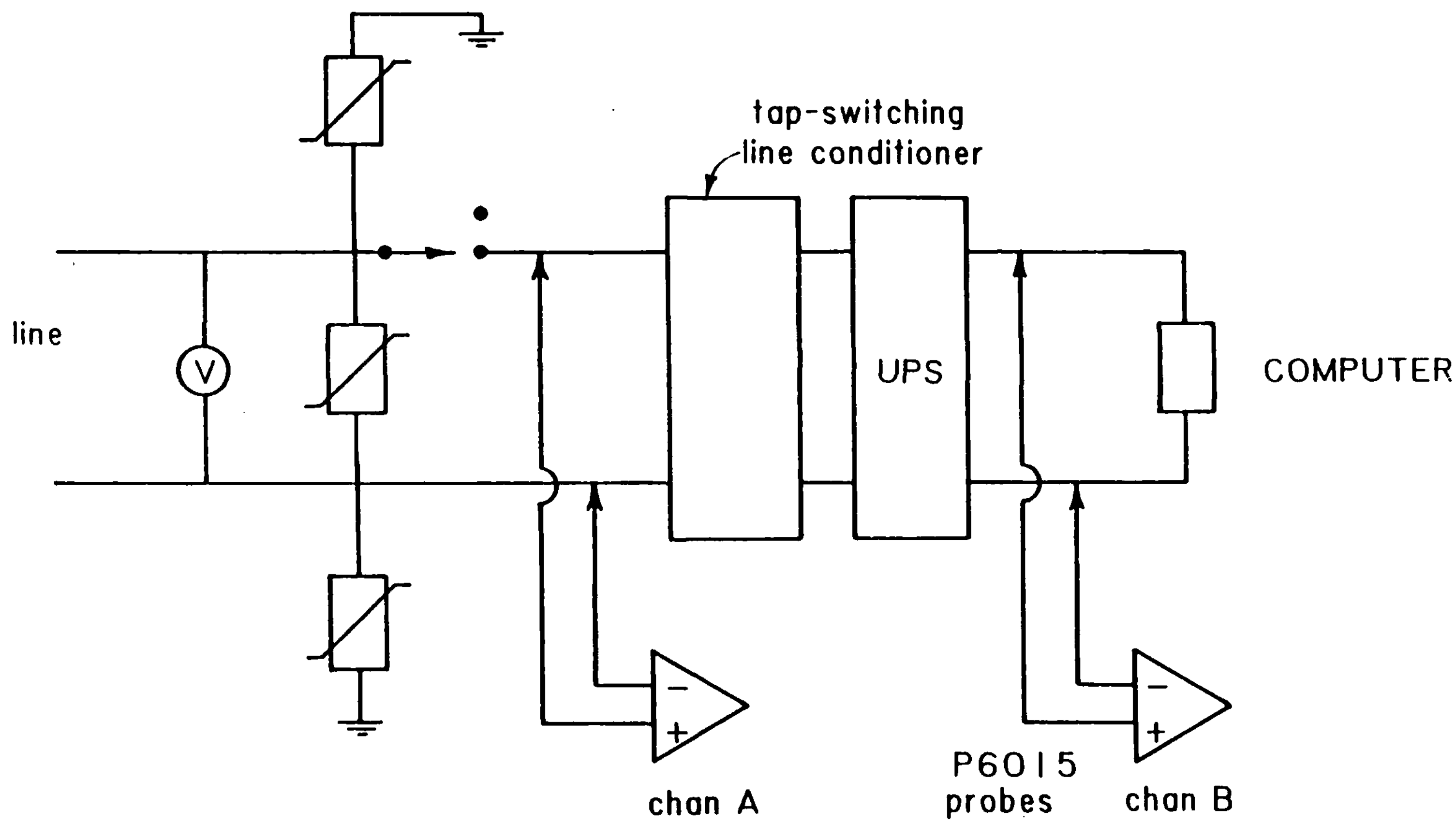


Figure 61. Tests with tap-switching conditioner upstream from UPS.

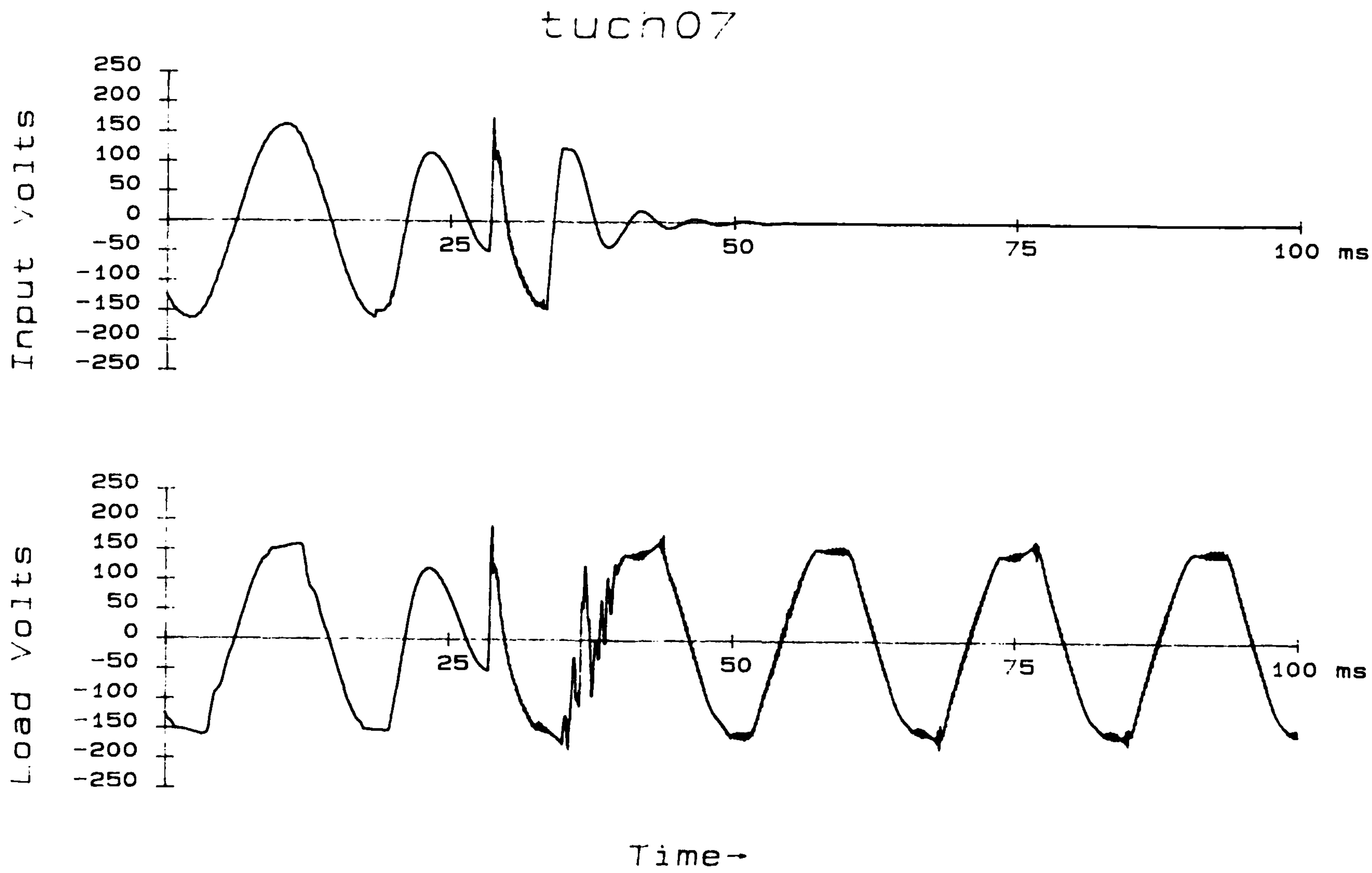


Figure 62. Topaz tap-switching conditioner upstream from standby UPS with an IBM PC/XT load; input voltage of conditioner and output voltage of UPS when the mains were switched off.

Figure 63 (file TUCJ04) shows the behavior of the Hewlett Packard 9836 computer in the circuit of Fig. 61. The mains were disconnected at 25 ms. The load voltage exceeded the 200 V full scale value of the digitizer at 33 ms. The noise on the load voltage after 40 ms is similar to Fig. 57 (file TUCJ02). The features and interpretation of Fig. 63 (file TUCJ04) are the same as Fig. 62 (file TUCH07).

UPS WITH FERRORESONANT CONDITIONER DOWNSTREAM

The experiments described above in Figs. 58 to 60 were repeated with the ferroresonant line conditioner downstream from the standby UPS. The test schematic is shown in Fig. 64. This circuit has the advantage that the line conditioner can remove any noise created by the inverter in the UPS. However there are two disadvantages:

1. During an outage the batteries in the UPS must supply power to keep the ferroresonant transformer's core in saturation.

2. When the ferroresonant transformer is turned on, the input current surge can trip the circuit breaker in the UPS.

Figure 65 (file TUCH03) shows the behavior of the system in Fig. 64when the IBM PC/XT is used as a load. The mains are switched off sometime between 33 ms and 37 ms. At 38.3 ms the input voltage of the UPS, which was an open circuit, exceeded the 200 V full scale of the digitizer. The cause of this transient may be the same as that of Fig. 42 (file SOBB03). The load voltage is remarkably clean due to the filtering action of the resonant circuit in the ferroresonant line conditioner.

Figure 66 (file TUCJ06) shows the behavior of the system in Fig. 64when the Hewlett Packard 9836 was used as a load. The mains are switched off at 21.6 ms. At 24 ms the input voltage of the UPS, which was an open circuit, exceeded the 200 V full scale of the digitizer. This transient has some of the features of Fig. 43 (file SOBA03). The major difference is that in Fig. 66 (file TUCJ06), the largest

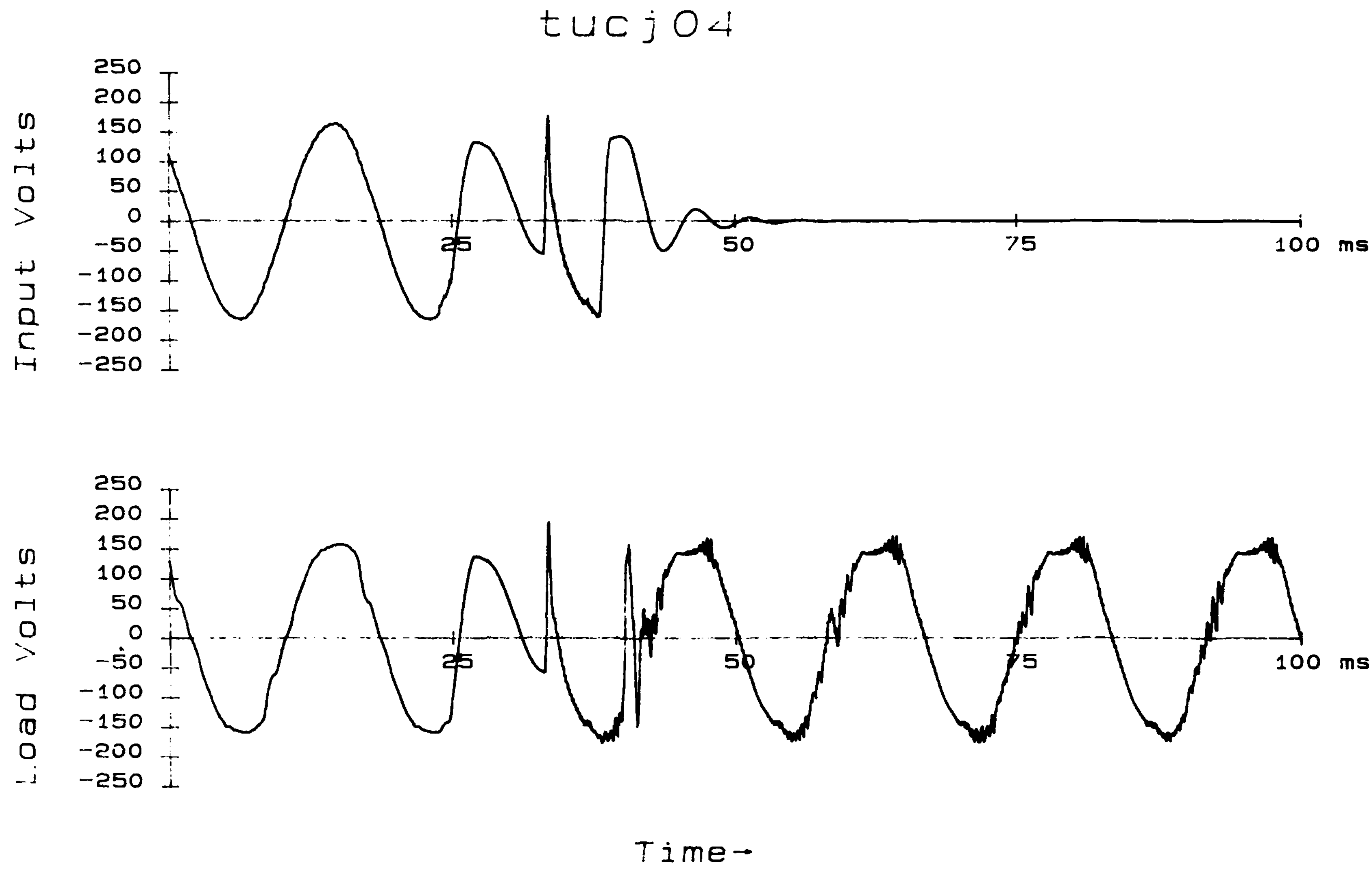


Figure 63. Topaz tap-switching conditioner upstream from standby UPS with an HP 9836 computer load; input voltage of conditioner and output voltage of UPS when the mains were switched off.

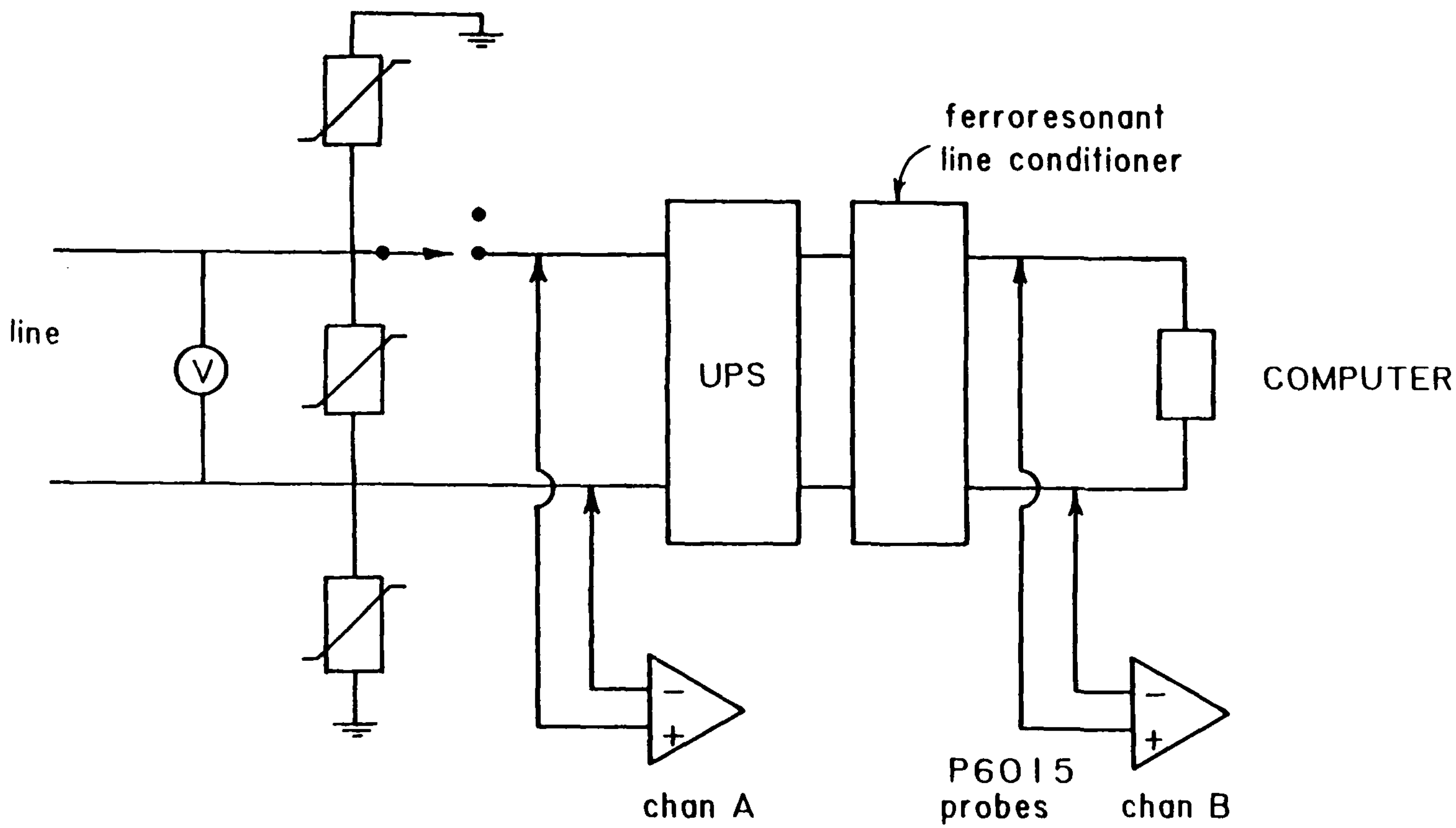


Figure 64. Tests with ferroresonant conditioner downstream from UPS.

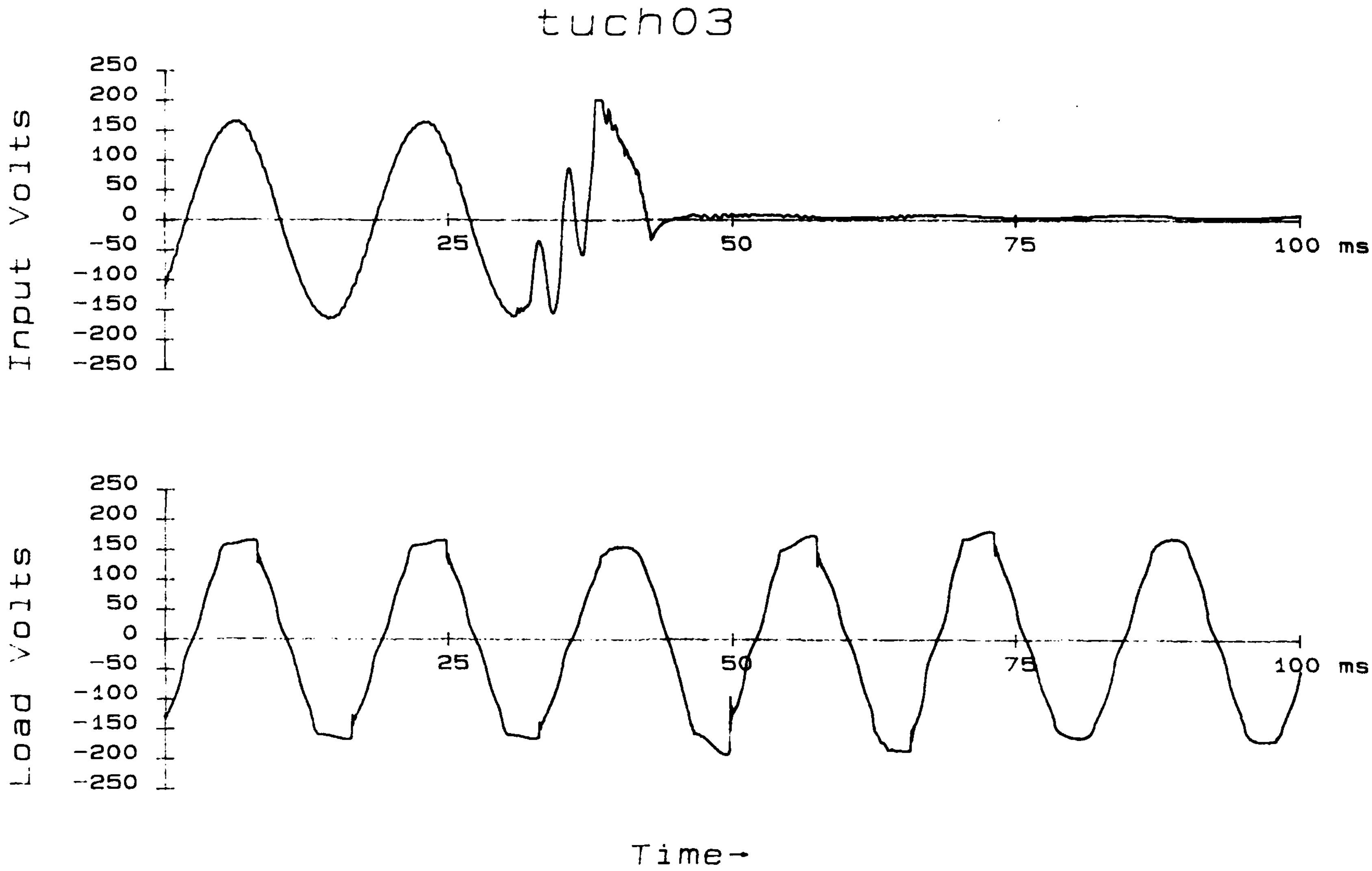


Figure 65. Sola ferroresonant conditioner downstream from standby UPS with an IBM PC/XT load; UPS input voltage and conditioner output voltage when the mains were switched off.

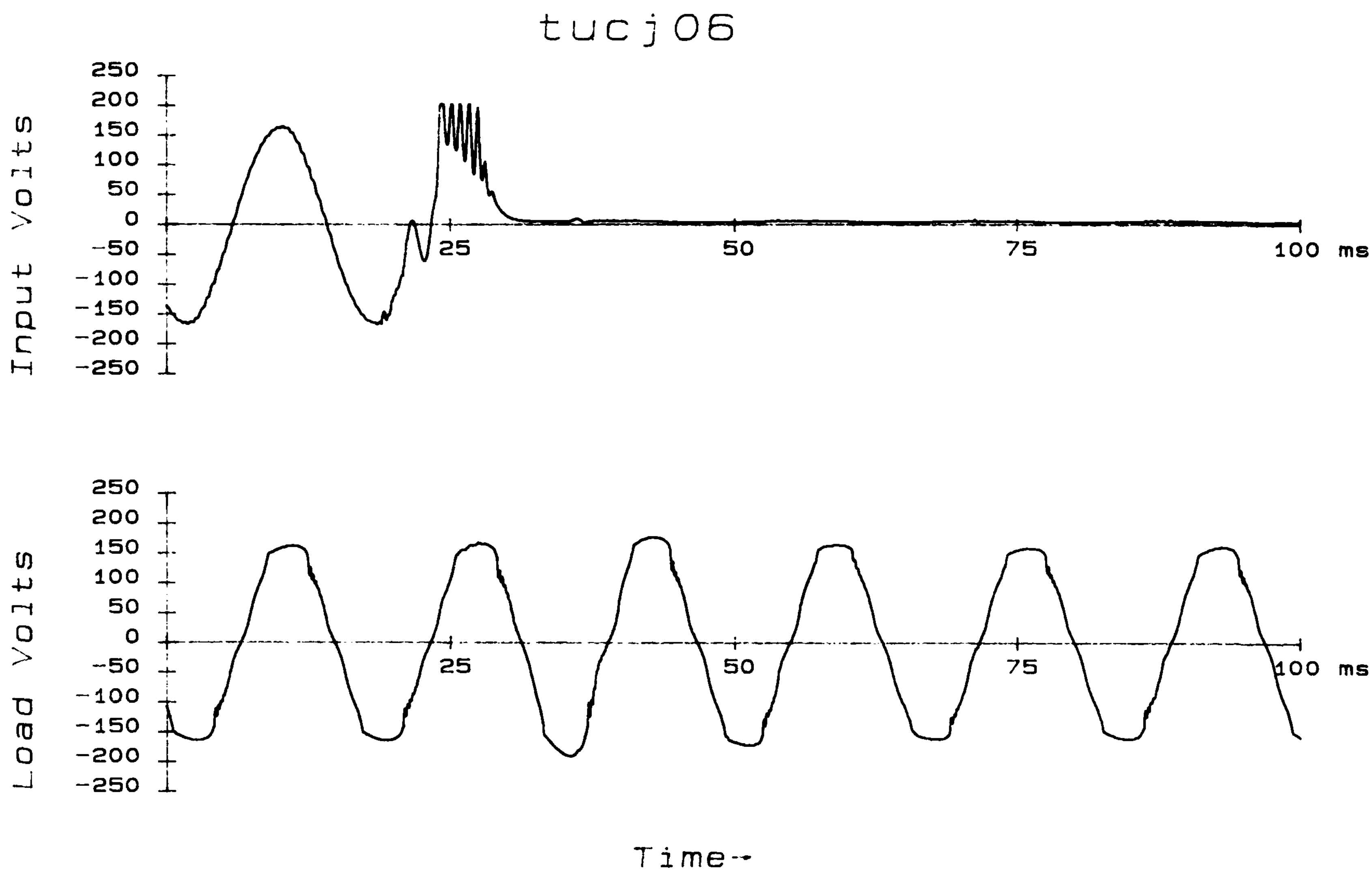


Figure 66. Sola ferroresonant conditioner downstream from standby UPS with an HP 9836 computer load; UPS input voltage and conditioner output voltage when the mains were switched off.

transient comes first, not last. The interpretation of the features of Fig. 66 (file TUCJ06) are the same as for Fig. 65 (file TUCH03), which was discussed above.

UPS WITH TAP-SWITCHING CONDITIONER DOWNSTREAM

Finally the ferroresonant line conditioner was replaced with the Topaz tap-switching line conditioner. The test schematic is shown in Fig. 67. This circuit was only tested with the IBM PC/XT as a load. The results are shown in Fig. 68 (file TUCH05). The mains were disconnected sometime between 31.9 ms and 41.8 ms. At 41.8 ms the input voltage of the UPS, which was an open circuit, exceeded the 200 V full scale of the digitizer. The load voltage during the UPS switching is not nearly as smooth as it was in Fig. 65 (file TUCH06), where the ferroresonant line conditioner was used.

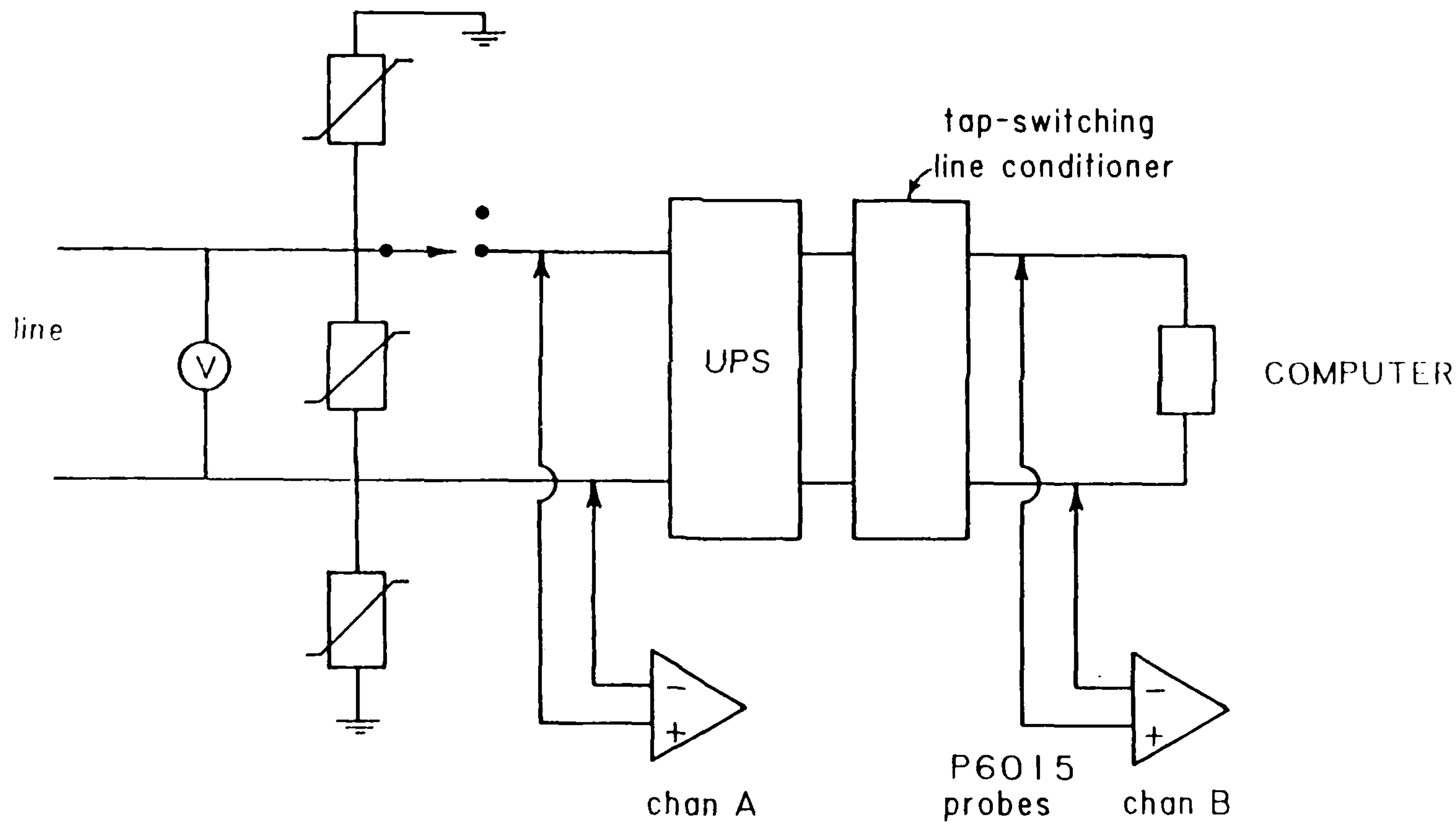


Figure 67. Tests with tap-switching conditioner downstream from UPS.

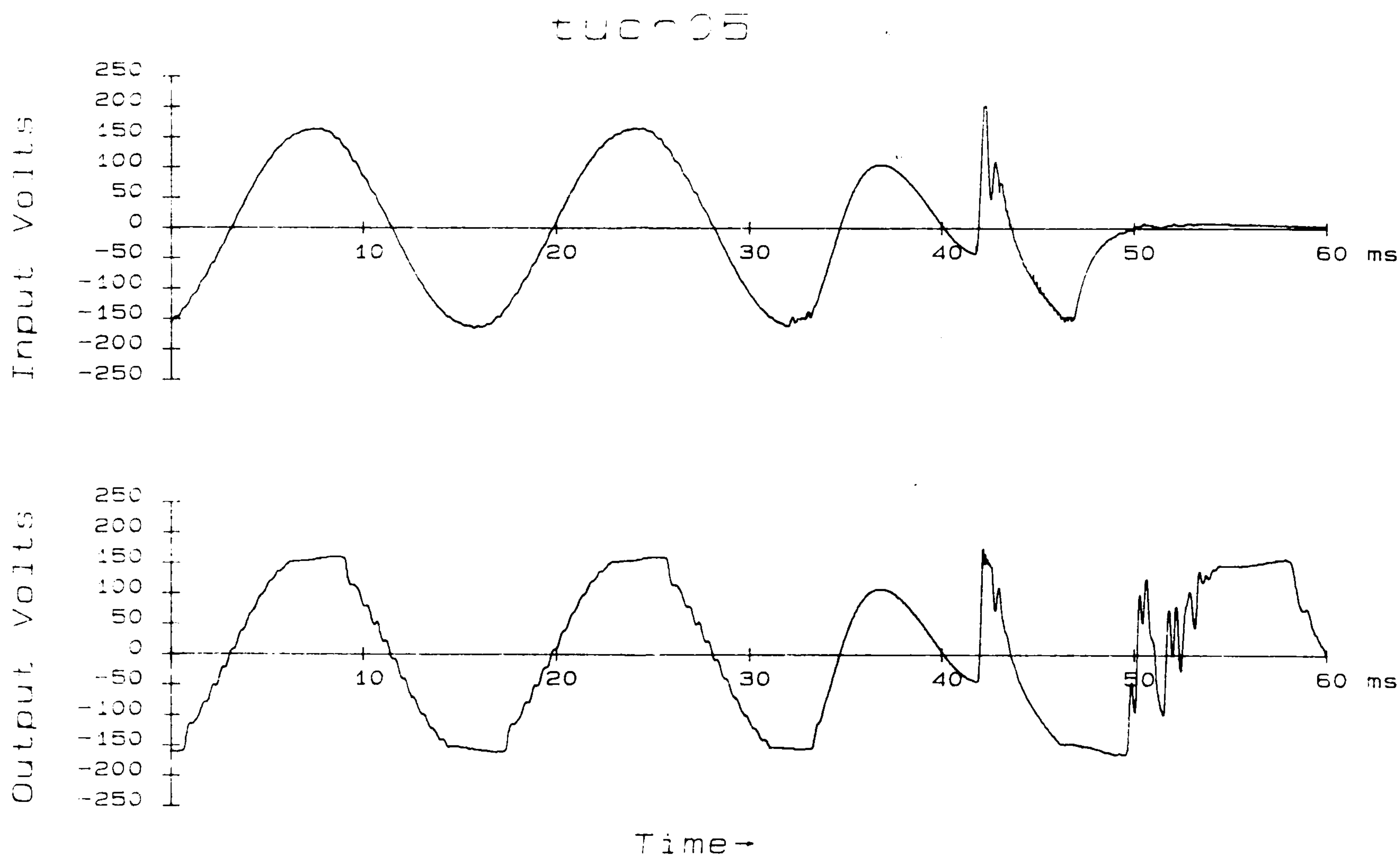


Figure 68. Topaz tap-switching conditioner downstream from a standby UPS with an IBM PC/XT load; UPS input voltage and conditioner output voltage when the mains were disconnected.

SECTION 7

INTRODUCTION TO HIGH VOLTAGE TESTS

The major effort in this research project was to study the effect of high voltage pulses on the output voltage of each line conditioner. Transient overvoltages were applied to the input terminals of the line conditioner. We used a transient digitizer to measure the input and output voltages of the line conditioner as a function of time.

All tests, except the 8x20 waveform, were conducted when the line conditioner under test was energized by the local 120 volt rms 60 Hz mains. Appropriate isolation and protection components, which are described in detail later, were inserted between the mains and the surge generator. The protection components prevented upset and damage to the digitizer and computer, as well as to other electronic equipment in the building. The isolation components kept th protection components from affecting the experiment.

Four different transient waveshapes were used. These had the following properties:

1. Ring wave (as specified in IEEE Standard 587, Category A). This voltage waveform has a linear rise to 6 kV open-circuit in 0.5 μs, followed by a damped sinusoidal oscillation at a frequency of 100 kHz.

2. 100 kV/μs rate of rise on initial linear voltage ramp, followed by damped oscillation. This waveform is useful for simulations of some HEMP effects.

3. 8 x 20 μs current waveform. This waveform has a linear rise to 500 A short-circuit current, followed by an exponential decay. This waveform is commonly used to test spark gaps and varistors.

4. Large pulses. A 2 μF capacitor was charged to approximately 5 kV, then discharged through a triggered spark gap. This test could provide peak short-circuit currents of the order of 10 kA and energy transfer of the order of 25 joules.

Transient overvoltages were applied to the device under test in both differential-mode and common-mode configurations. Figure 69 illustrates the definition of differential-mode and common-mode for the tests. The ring wave tests, which had a relatively small energy content, were coupled to the power line with a transformer. For the pulses with large energy transfer, as described later, metal oxide varistors were used to couple the pulse generator to the 60 Hz mains. Details about the pulse generator and test circuit are presented immediately before the results from each group of tests.

Six different loads were available during the high voltage pulse testing:

1. 35 Ω resistor (410 watts at 120 V rms),
2. 75 Ω resistor (190 watts at 120 V rms),
3. 150 Ω resistor (100 watts at 120 V rms),
4. 15 μF capacitor (80 VAR at 120 V rms, 60 Hz),
5. 1/12 hp motor, no mechanical load,
6. open circuit.

These loads allowed simulation of both resistive and reactive loading conditions. The line conditioners were rated by their manufacturers for a maximum load of 500 VA. The 35 Ω resistor provided 80% of the maximum rated load. Other loads provided lighter loading.

All line conditioners that were included in this study have a captive three wire cable for connection to the mains with a standard National Electrical Manufacturers Association (NEMA) type 5-15P plug on the end. The high voltage transients were applied to the plug at the end of this cable in order to properly simulate actual user

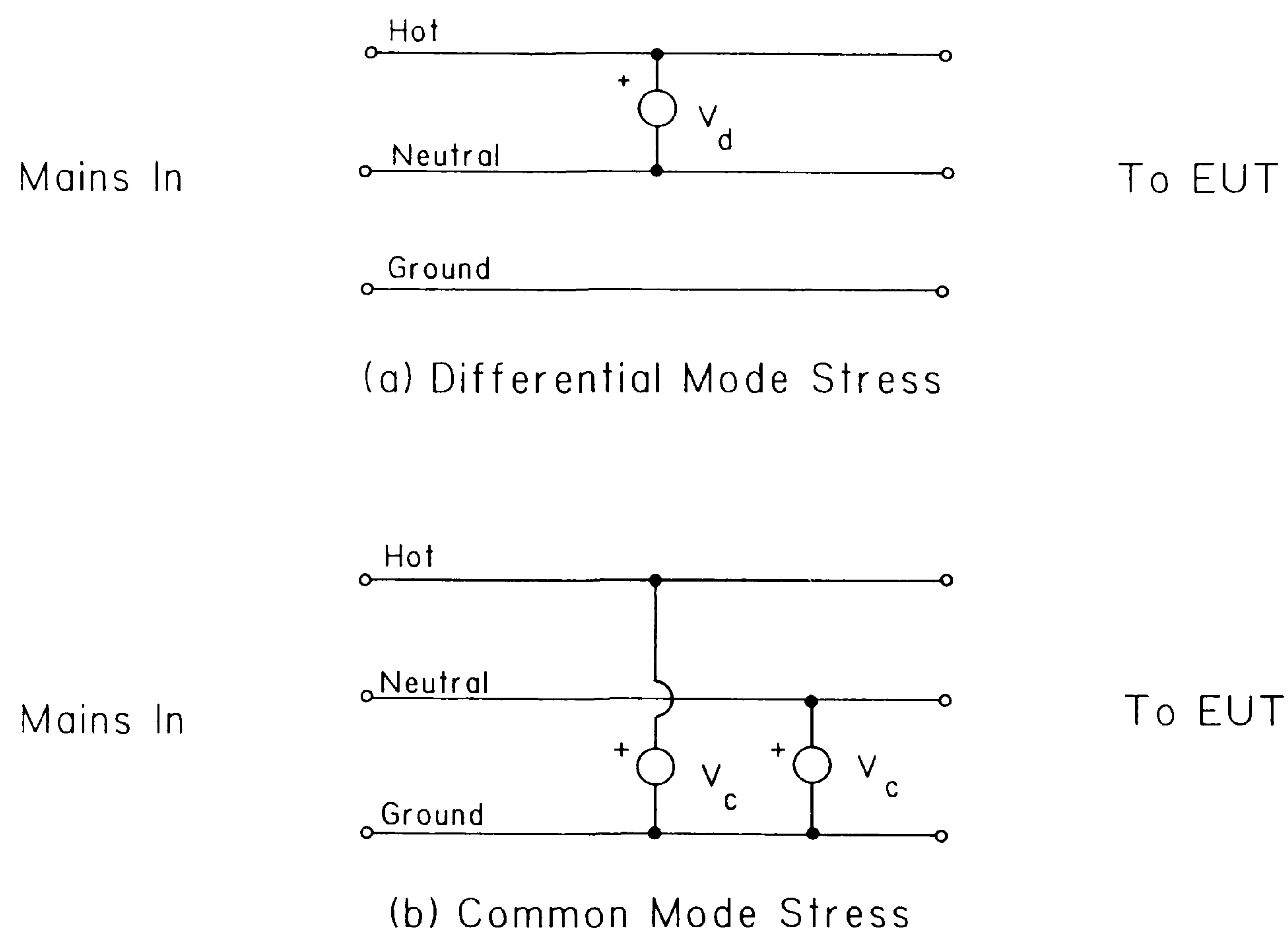


Figure 69. Differential-mode and common-mode transients.

conditions. An alternate method would have been to disassemble the line conditioners and apply the high voltage pulse internally. The alternate method has the advantage that shorter risetimes could be achieved, but it does not represent actual usage.

In order to reduce the electromagnetic radiation from the input cable, plastic cable ties were used to tightly bunch the cable as shown in Fig. 70. The input cable presented minimal loop area and the effective length for radiation was shortened considerably.

RING WAVE TEST METHODS

The standard test waveform for surge testing equipment on the power line is a ring wave as prescribed in ANSI Standard C62.41-1980 (also called IEEE Standard 587-1980). The open-circuit voltage waveform is given in Eq. 2.

$$V(t) = (1.59 * V_p) \{1 - \exp(-t/0.533\ \mu s)\} \exp(-t/9.79\ \mu s) \cos(\omega t) \tag{2}$$

where $\omega = 6.28 \times 10^5$ rad/s.

The test circuit is shown in Fig. 71. The transient was generated and coupled to the power line by a Keytek Model 424 surge generator with a model PN281LSC plug-in unit.

The line voltage was measured with a matched pair of Tektronix P6015 probes that were connected to a Tektronix 7A13 differential amplifier in the Tektronix 7612D digitizer. Each probe was compensated in the usual way with a 30 V peak-to-peak square wave at 10 kHz from a function generator. Then both probes were connected to the same signal, the amplifier was set to the difference function, and the compensation of the probe at the inverting input was adjusted to give the minimum amplitude at the output of the 7A13 amplifier. This procedure maximized the common-mode rejection ratio (CMRR) of our measurements. We were able to obtain a CMRR value of -35 dB.

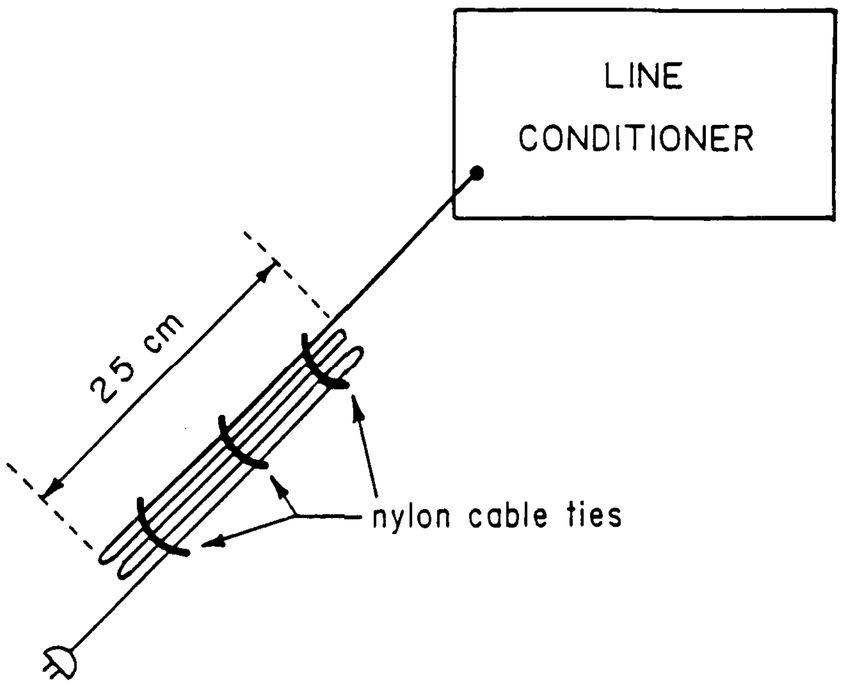


Figure 70. Arrangement of line cords.

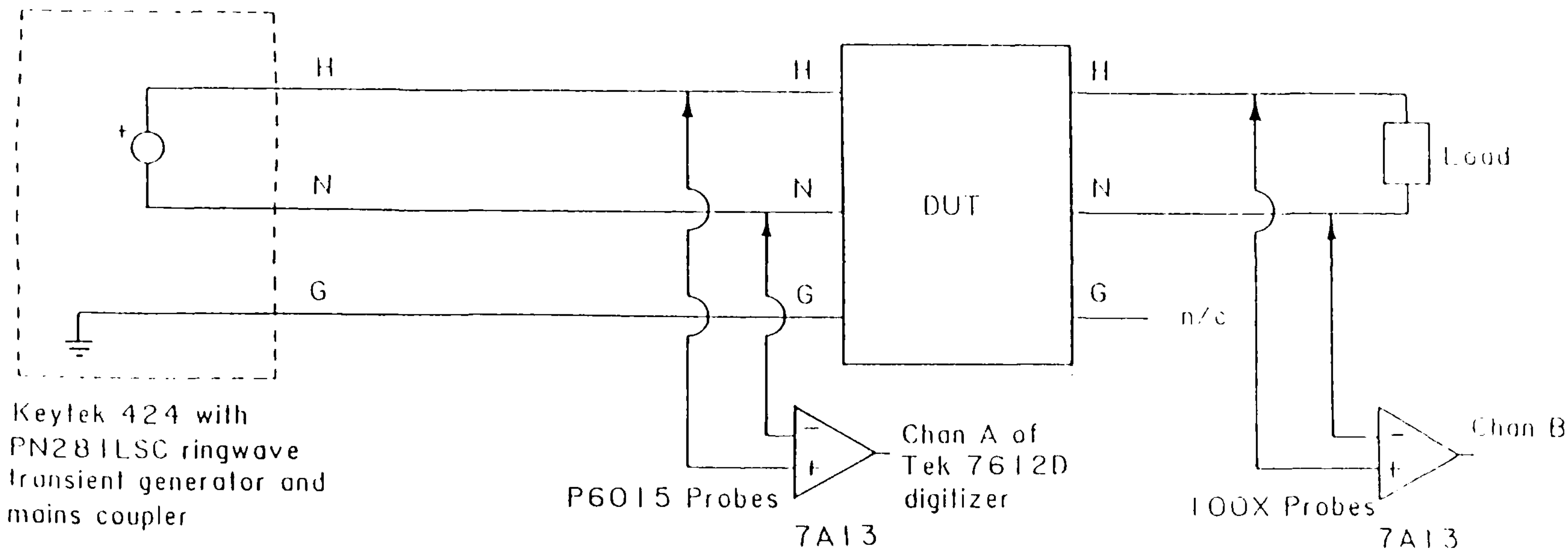


Figure 71. Differential-mode ring wave test schematic.

By using two differential amplifiers and four probes, connections between the input and output circuits were avoided. This avoided errors associated with differences of "ground" potential caused by large pulse currents flowing in wires with resistance and inductance.

The output voltage from the device under test was measured in a similar way with Tektronix P6007 and P6009 probes. A CMRR value of -40 dB was obtained with these probes when measuring a 30 V peak-to-peak square wave.

The digitizer was usually set to acquire data simultaneously from both channels at a rate of 20 samples per microsecond. There were 2048 consecutive samples in a record, which gave a time interval of 102.4 μs. When large spikes were observed in the record at the usual sample rate, the test was repeated with a sampling rate of 200 samples per microsecond, which gave a 10.24 μs record length.

We used various sensitivities of the 7A13 amplifiers during these experiments. Common settings were 2 kV/div for the input and 100 V/div for the output. The digitizer provided a resolution of 32 bits per vertical division. Noise present in the amplifier and digitizer appears in the digital record as fluctuations of one or two least significant bits (LSB). This quantization noise is not found on the screen of analog oscilloscopes and so appears strange to engineers who are not accustomed to viewing digital records.

DIFFERENTIAL-MODE RING WAVE TEST RESULTS

The line conditioners were initially tested with a peak open-circuit voltage, V_p, of about 1 kV applied to the input of each device under test. Both the input and output voltages were measured. All of the devices performed well during these initial tests, so the peak open-circuit voltage, V_p, was increased to 6 kV. This stress is suggested by ANSI Standard C62.41 to represent the indoor environment at outlets that are located more than 10 m from major feeders and more than 20 m from the point of entry to the building.

A representative set of data is shown in Fig. 72 (file SORB00). A ring wave with a peak of 6.3 kV was applied to the input cable of the Sola ferroresonant line conditioner at the positive peak of the mainsvoltage. A small excursion of ±35 V was measured at the output of the line conditioner during this test. The essentially constant 121 V offset in Fig. 72 (file SORB00) is due to the 60 Hz sinusoidal mains voltage. (During the 102 μs duration of this record, the mains voltage changes by less than 5 V.) The output of the ferroresonant line conditioner is not at the positive peak of the mains voltage, about 170 V, due to phase shift in the line conditioner. This experiment was repeated with a faster sampling rate, and the results are shown in Fig. 73 (file SORB06).

We repeated the tests with each of the following loads:

1. 35 Ω resistor (410 W at 120 V rms),
2. 150 Ω resistor (96 W at 120 V rms),
3. 15 μF capacitor (80 VAR at 120 V rms, 60 Hz),
4. 1/12 hp motor, with no mechanical load,
5. no load.

For most line conditioners, changing the load produced insignificant effect in the output voltage during the transient. The one exception is discussed later.

The transient overvoltage was selected to have a positive first peak and was commonly applied at the positive peak of the 60 Hz sinusoidal mains voltage. Additional experiments were performed with the transient applied at a zero-crossing of the 60 Hz sinusoidal mains voltage. When the overvoltage was applied with a variety of line conditioners and loads, no significant effect was seen, due to the phase angle of the mains voltage.

These ring wave tests were the mildest stresses applied during this research project. Not surprisingly, all of the line conditioners

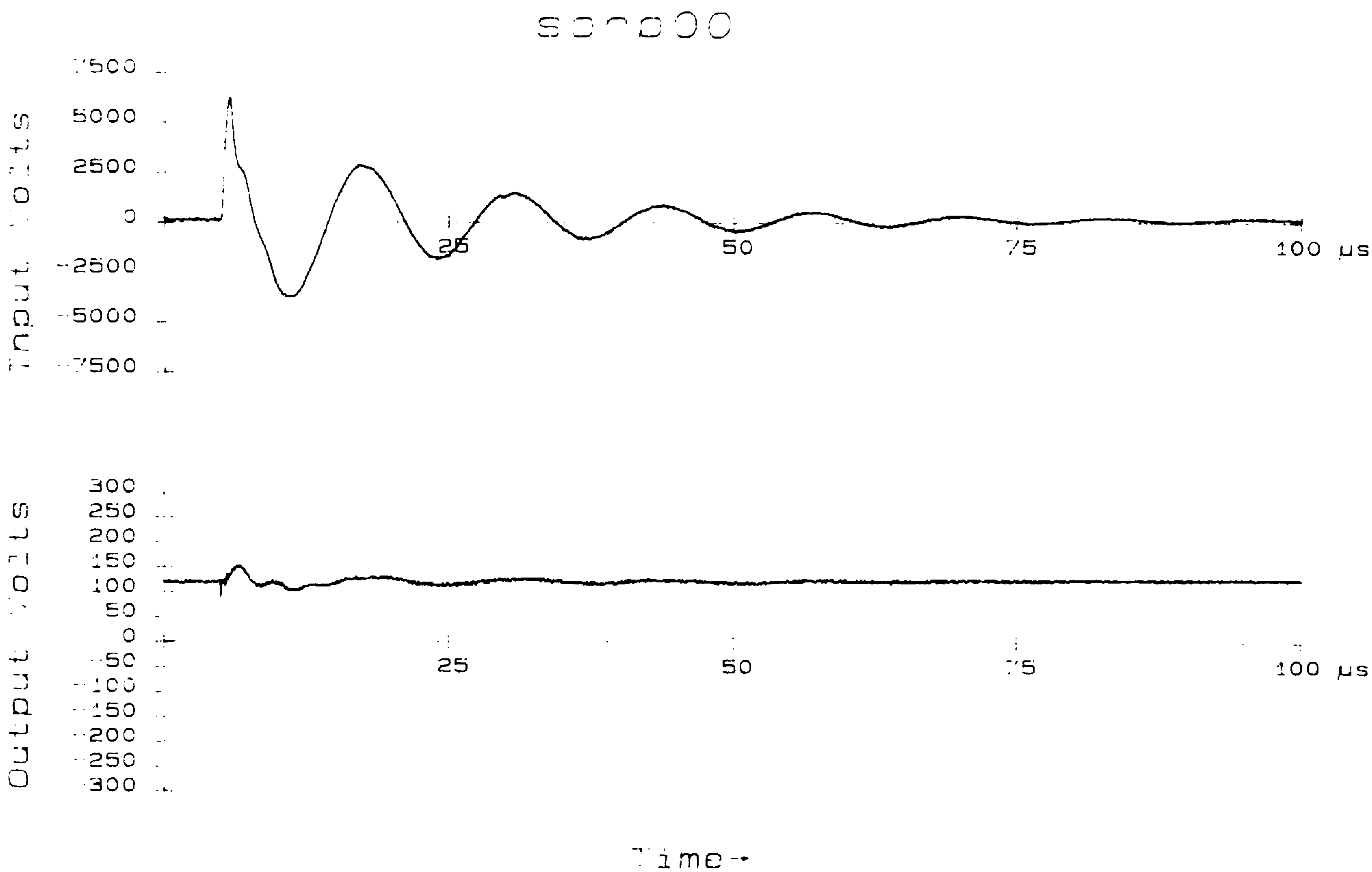


Figure 72. Differential-mode ring wave test of a Sola ferroresonant conditioner with a 35 Ω load.

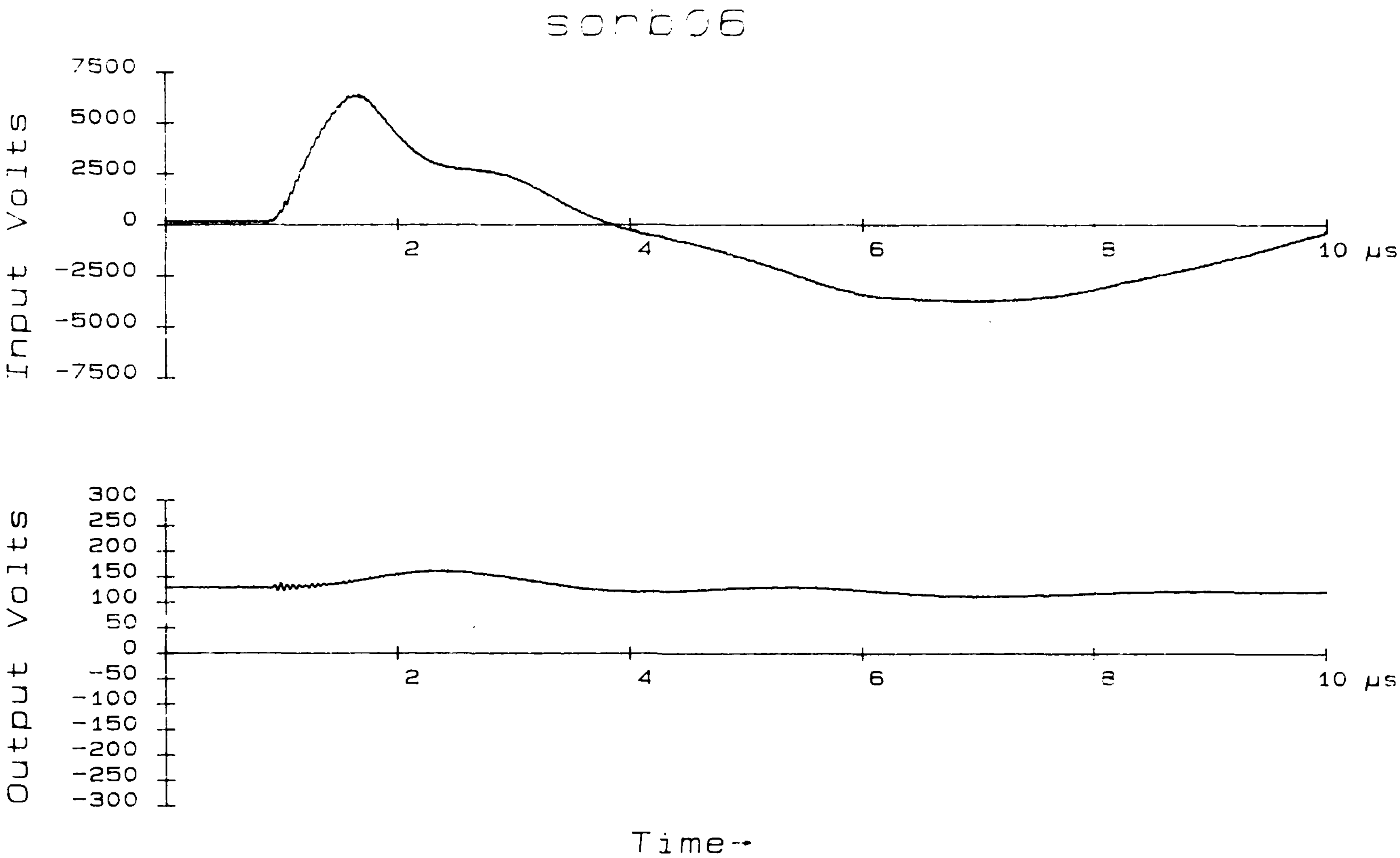


Figure 73. Differential-mode ring wave test of a Sola ferroresonant conditioner with a 35 Ω load.

usually performed well even without MOVs connected upstream. The change in the output voltage was usually no more than ±30 V for a ring wave with a 6 kV peak, open-circuit. This change in output voltage should cause no concern.

When the surge generator was set to provide a 6 kV peak voltage into an open circuit, it also provided nearly 6 kV peak voltage when all but one of the line conditioners were connected to the circuit. When the Deltec tap-switching line conditioner was connected, the 6 kV peak open-circuit voltage was reduced to less than 1 kV. This reduction is stress was due to the small input impedance of the Deltec tap-switching line conditioner at high frequencies. In order to measure the input impedance during a transient, an Ion Physics Model CM-1-S current transformer was connected to the channel of the digitizer that was normally used for output voltage. This allowed simultaneous measurement of the input voltage and current to the line conditioner. Data were taken with surges applied between the hot and neutral conductors with the surge at the positive peak of the 60 Hz sinusoidal mains voltage. A 35 Ω resistive load was connected to the output of the device under test. The peak voltage divided by the peak current gives a measure of the input impedance of each device. The results are given in Table 4.

TABLE 4. APPROXIMATE INPUT RESISTANCE OF LINE CONDITIONERS

Sola ferroresonant	550 Ω
Topaz tap-switcher	650 Ω
Deltec tap-switcher	10 Ω

The transient output voltage of the Deltec tap-switching line conditioner was relatively large, as shown in Fig. 74 (file DERB03). Metal-oxide varistors (MOVs) connected at the output port would be ineffective in reducing the amplitude of this transient because the peak output voltage is only 160 V, about the same as the peak 60 Hz

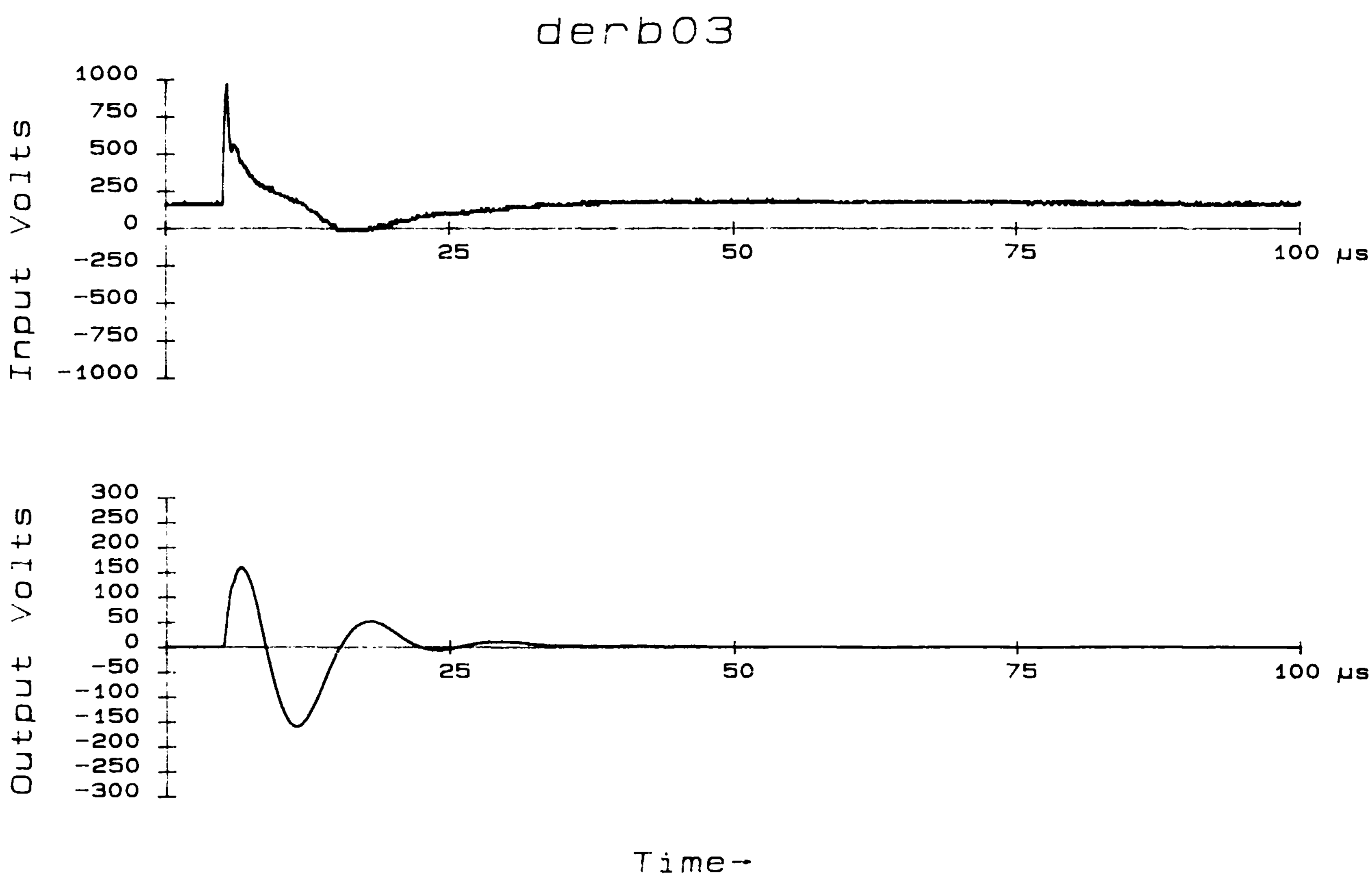


Figure 74. Differential-mode ring wave test of a Deltec tap-switching conditioner with a 150 Ω load.

sinusoidal mains voltage. However, MOVs connected upstream from the line conditioner would be effective in reducing the transient output voltage, as will be discussed later. MOVs will reduce the transient voltage seen by the input of the line conditioner by clamping the magnitude of the input voltage to less than 400 V. Since a smaller transient appears at the input port, the transient will also be smaller at the output port when MOVs are connected upstream from the conditioner.

The relatively large output voltage of the Deltec tap-switching line conditioner is not a generic feature of tap-switching line conditioners. The response of the Topaz line conditioner alone (without MOVs) under conditions similar to those of Fig. 74 (file DERB03) is shown in Fig. 75 (file TORK02).

While the output voltage excursion in Fig. 74 is definitely larger than in Fig. 75, the difference may have little practical significance. The authors of this report believe that MOVs should be connected upstream from all line conditioners in order to protect the line conditioner and to attenuate transients at the output.

The ferroresonant line conditioner was tested extensively to determine effects of loading on output waveform due to the theoretical concern that a reactive load might affect the resonant output circuit of the ferroresonant line conditioner. It was mentioned earlier that the load had little effect on the transient output voltage of the devices under test, with one exception. The output of the ferroresonant line conditioner in this test had a relatively large transient output voltage when a motor was connected as a load. Fig. 76 (file SORF02) shows a peak output voltage of 325 V for a 6.3 kV peak input voltage applied at the positive peak of the 60 Hz sinusoidal mains voltage, while a 1/12 hp motor was connected to the output. This peak is not shown in Fig. 76, since all of the figures were plotted with the same scale for convenient comparisons between and among figures. This large output voltage of the ferroresonant line conditioner is undesirable; however, this is not necessarily a

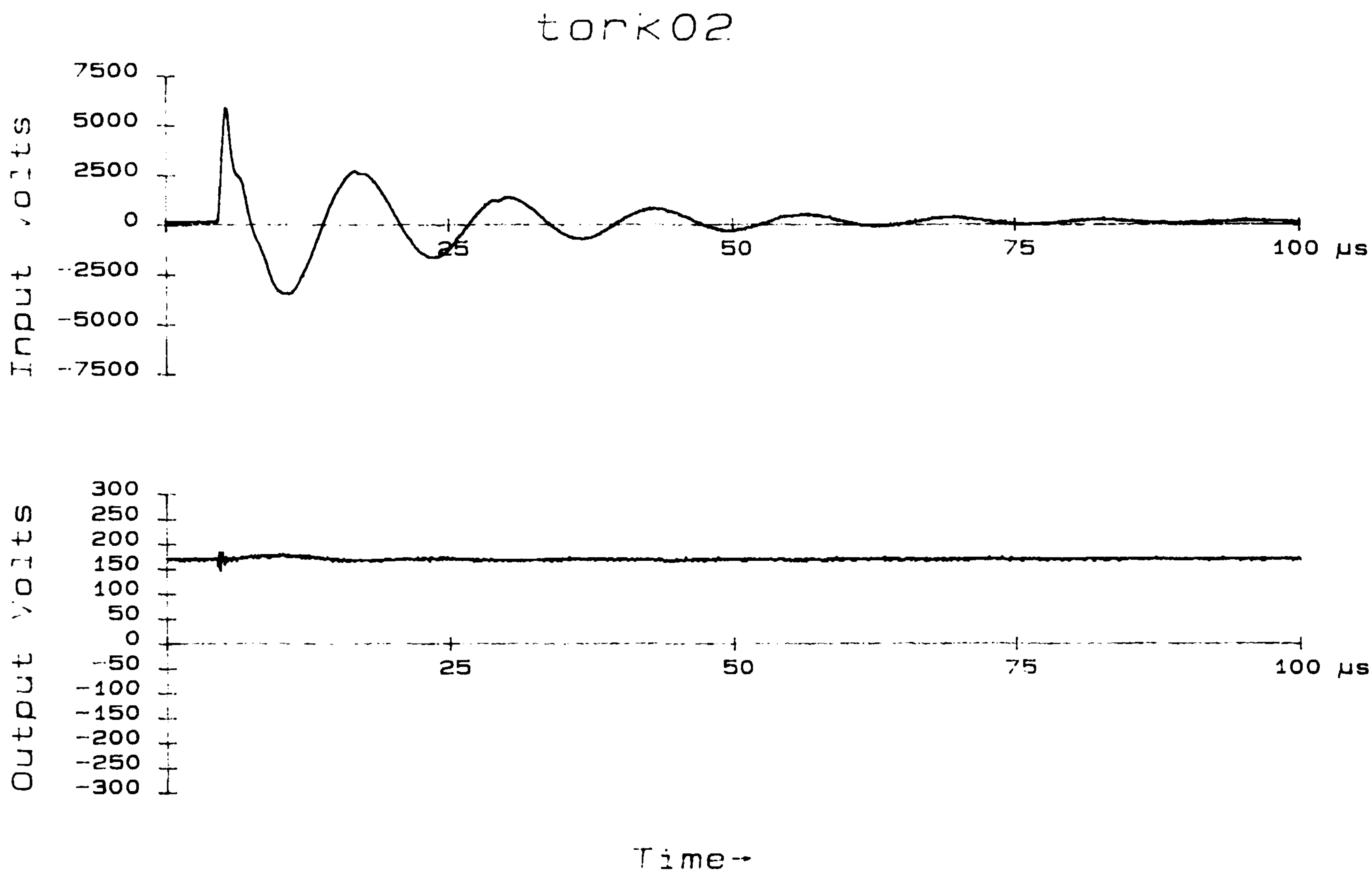


Figure 75. Differential-mode ring wave test of a Topaz tap-switching conditioner with a 150 Ω load.

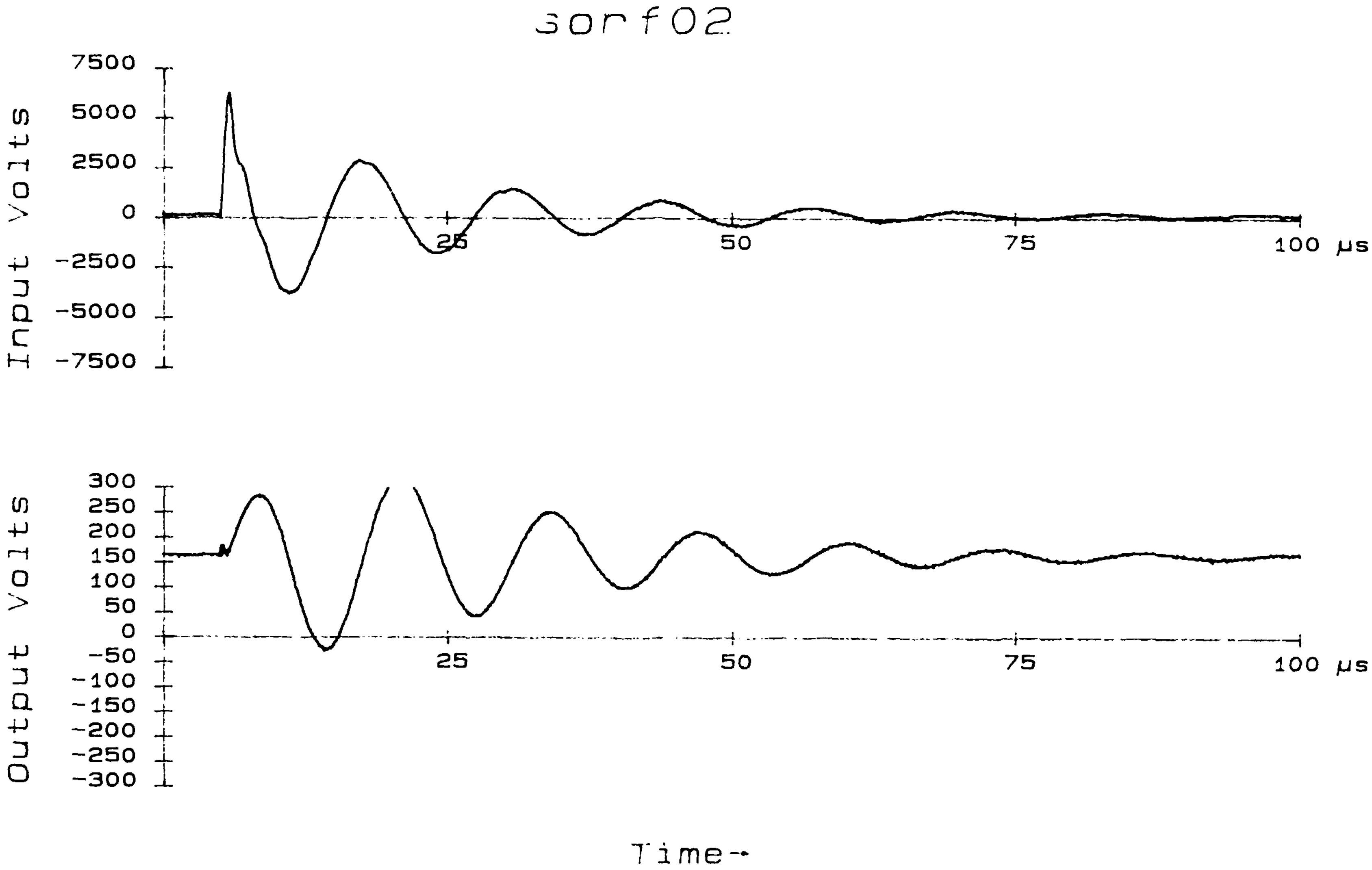


Figure 76. Differential-mode ring wave test of a Sola ferroresonant conditioner with a motor load.

criticism of the ferroresonant line conditioner. The authors of this report believe that metal oxide varistors (MOVs) should be connected upstream from any line conditioner.

The Oneac device attenuated differential-mode ring waves as shown in Fig. 77 (file ONRB09).

COMMON-MODE RING WAVE TESTS

When the transient voltage was applied between hot and neutral conductors, which is called a differential-mode transient, we measured the voltages between hot and neutral conductors as just described. Transients were also applied simultaneously to both the hot and neutral conductors with respect to ground, which is called a common-mode transient. During common-mode transients the voltage between the hot conductor and local ground in the power line were measured as shown in Fig. 78. Except for the connection of the reference voltage probes and the connection of the transient generator, the test schematic is identical to that for the differential-mode transients that were just discussed.

During the common-mode tests all of the devices under test showed a high-frequency ringing at their output port. Data were collected at the maximum sampling rate of the digitizer to resolve this ringing. Plots of input and output voltage for the three line conditioners are shown in Figs. 79, 80, and 81 (files SOSB03, TOSB01, and DESB03). The data in these three figures were taken under the same conditions of loading and surge generator parameters.

The ferroresonant line conditioner gave greater attenuation of the transient than either tap-switching line conditioner. The output excursion for all three line conditioners could be further reduced by connecting MOVs upstream from the line conditioner, as recommended in this report.

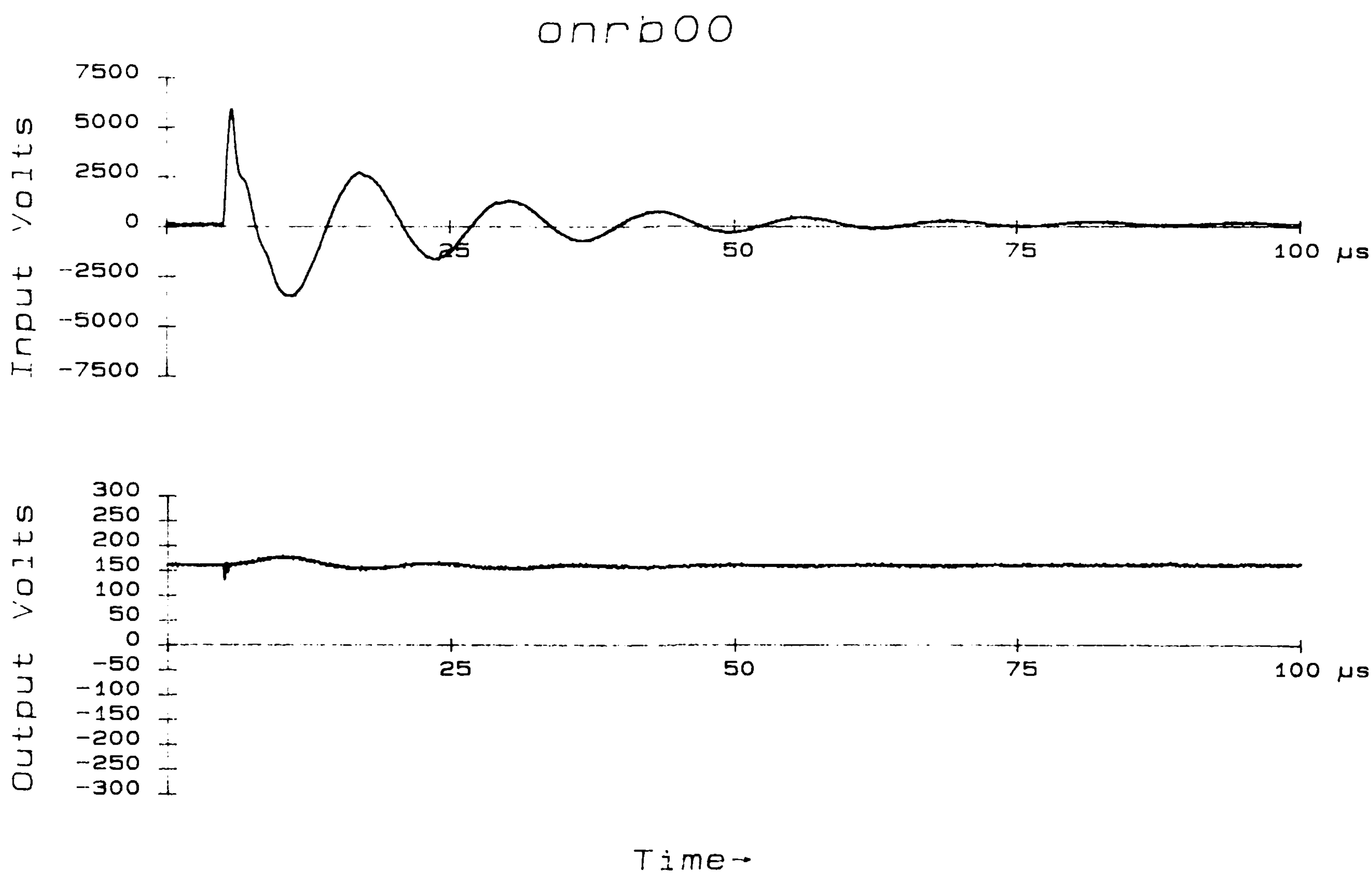


Figure 77. Differential-mode ring wave test of an Oneac device with a 35 Ω load.

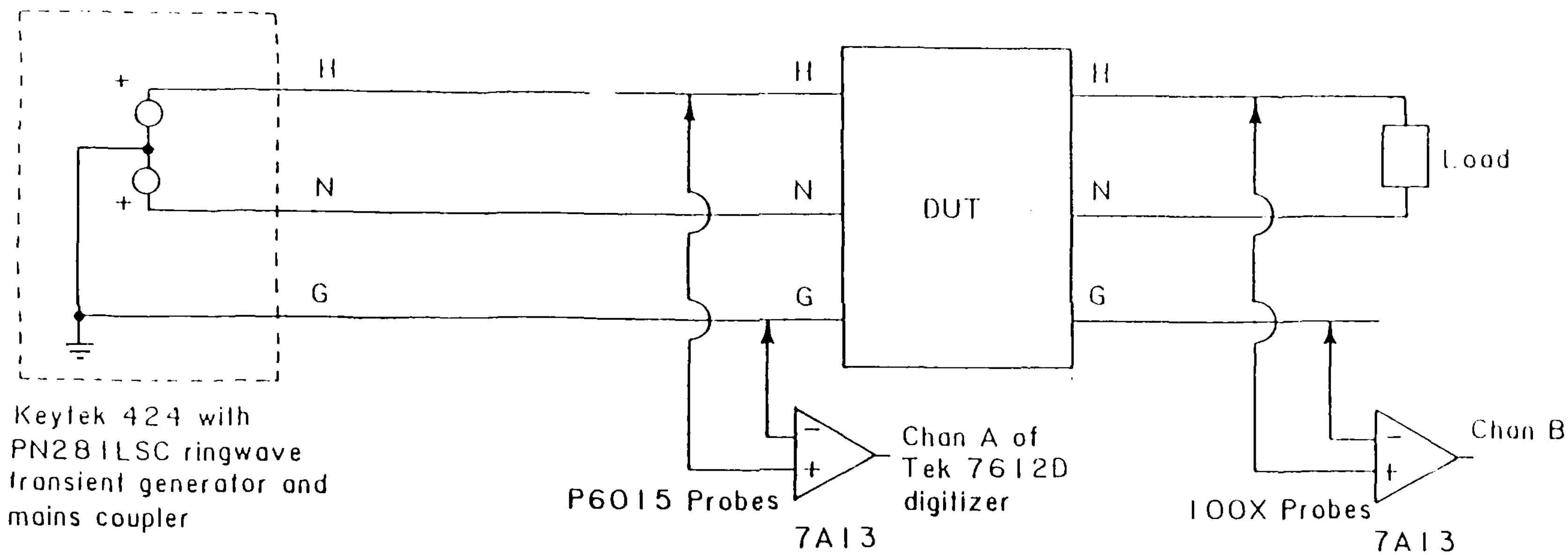


Figure 78. Common-mode ring wave test schematic.

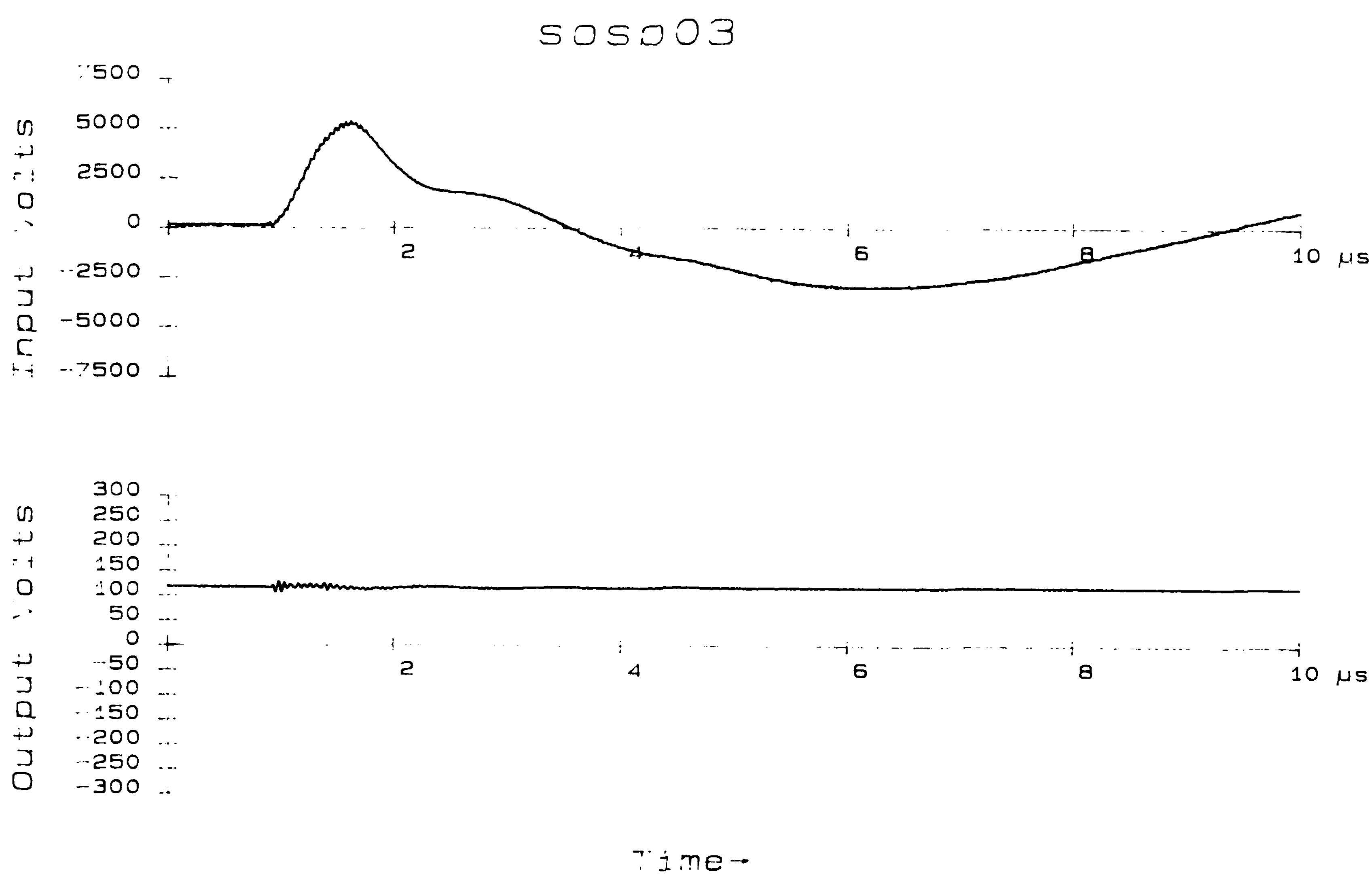


Figure 79. Common-mode ring wave test of a Sola ferroresonant conditioner with a 35 Ω load.

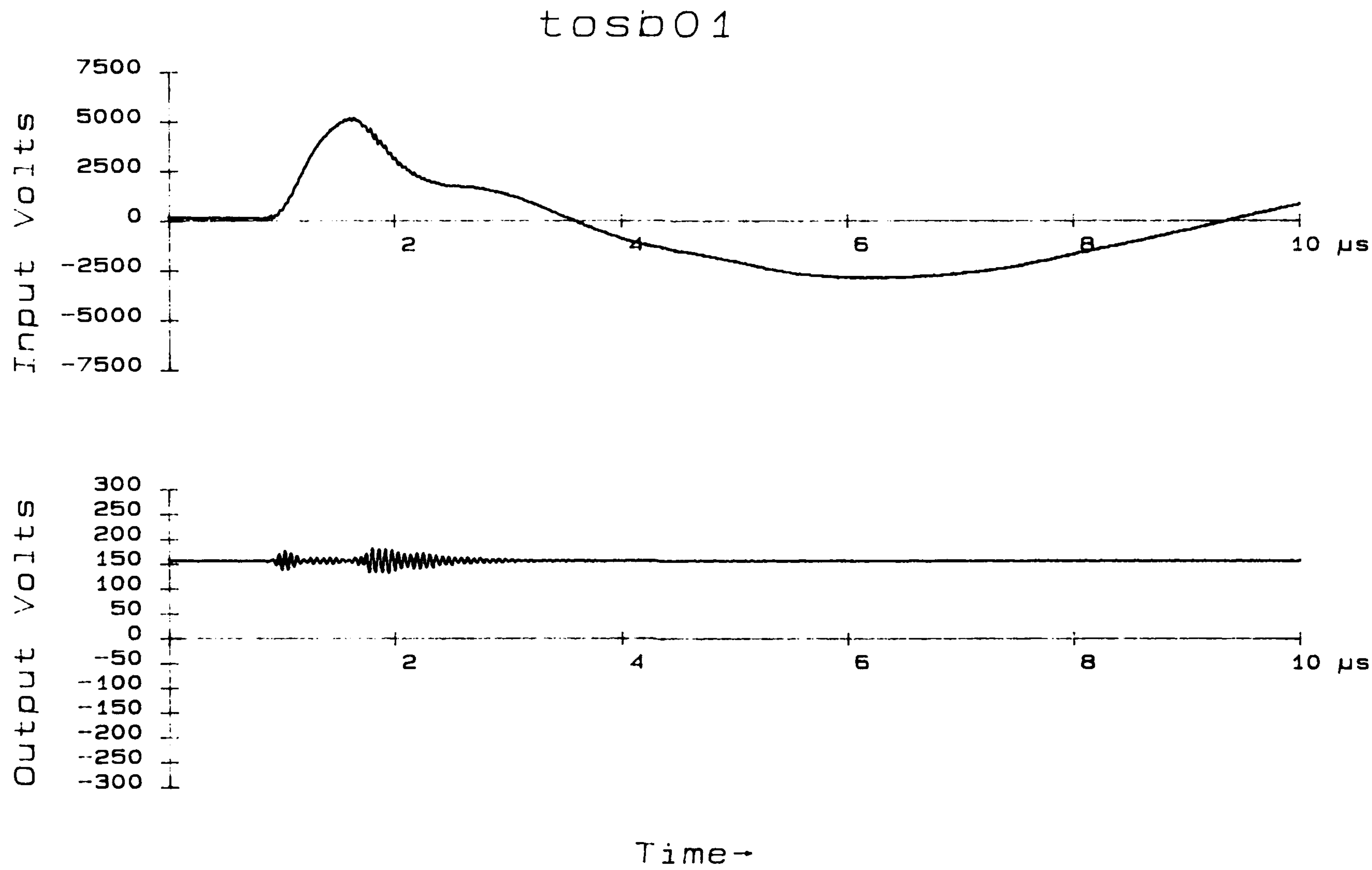


Figure 80. Common-mode ring wave test of a Topaz tap-switching conditioner with a 35 Ω load.

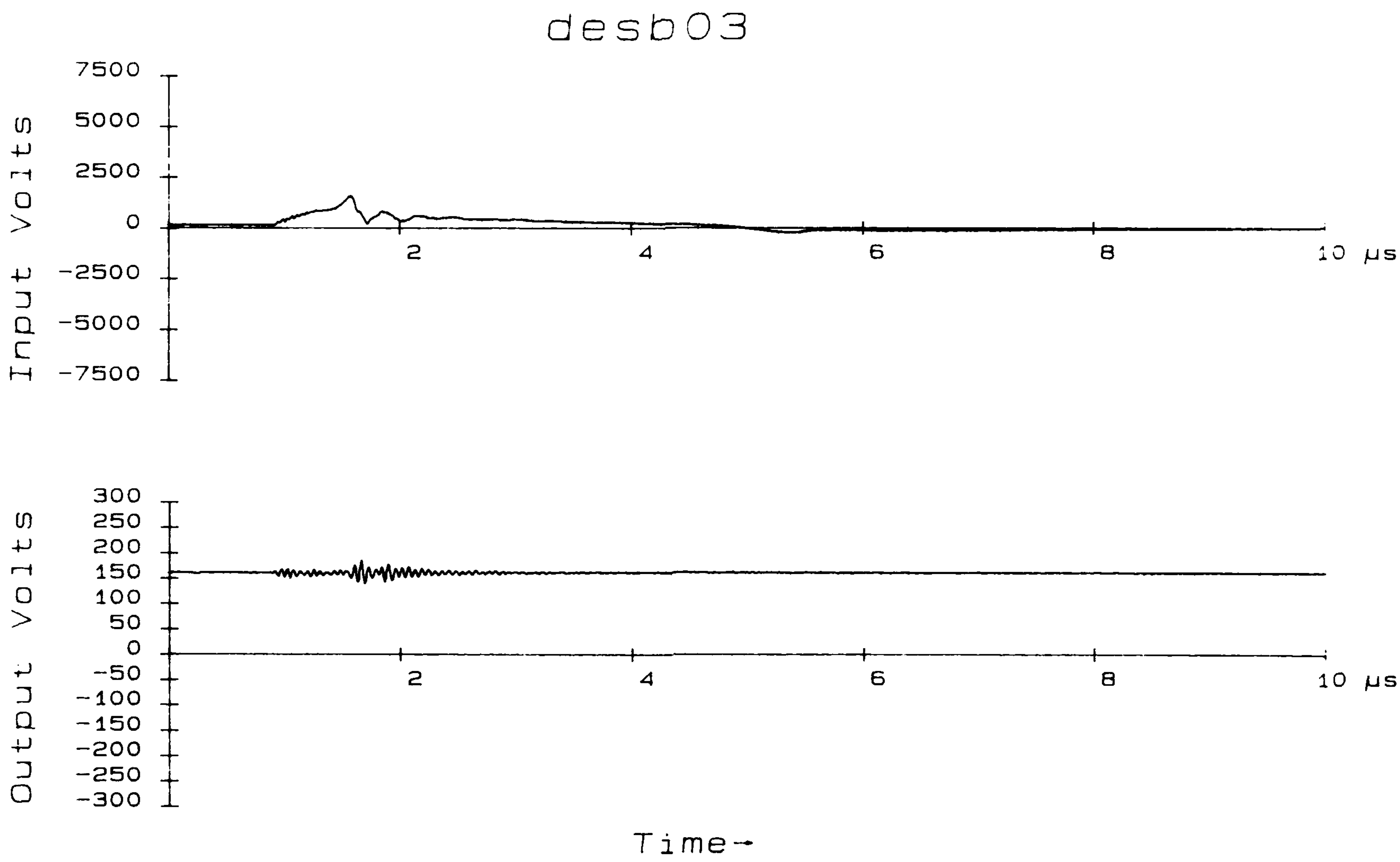


Figure 81. Common-mode ring wave test of a Deltec tap-switching conditioner with a 35 Ω load.

The Deltec line conditioner presented a relatively small input impedance to the common-mode transient, which reduced the magnitude of the transient voltage due to the output impedance of the generator.

Tests were repeated with various loads and phase angles, as described above for differential-mode transients. No effects due to phase of the 60 Hz sinusoidal waveform were observed. Effects due to different loads at the output of the device under test were examined. The Deltec tap-switching line conditioner had larger transient output voltage when a 150 Ω resistive load was connected than when a 35 Ω load was connected. The behavior of the Topaz tap-switching line conditioner with 35 Ω and 150 Ω loads was opposite that of the Deltec unit, so no generalizations can be made about tap-switching devices.

Output voltage excursions when a motor load was connected to the ferroresonant line conditioner were similar to those seen when a resistive load was connected.

The Oneac device, while not a line conditioner, did attenuate common-mode transients as shown in Fig. 82 (file ONSB00).

"EMP WAVEFORM"

The Keytek Model 424 generator and PN253 waveshaping plug-in can generate transients with an open-circuit voltage of 1.5 kV and a risetime of 0.015 μs. These rapidly rising voltages are useful to simulate some EMP effects and some effects of direct lightning strikes. We used this generator on its maximum output setting, which could transfer 16 joules of energy to the test circuit.

The input voltage was measured in the same way used for ring waves, which were discussed previously.

The output voltage was measured with a matched pair of Tektronix P6055 probes and a Tektronix 7A13 differential amplifier. These probes are designed by the manufacturer for use in differential

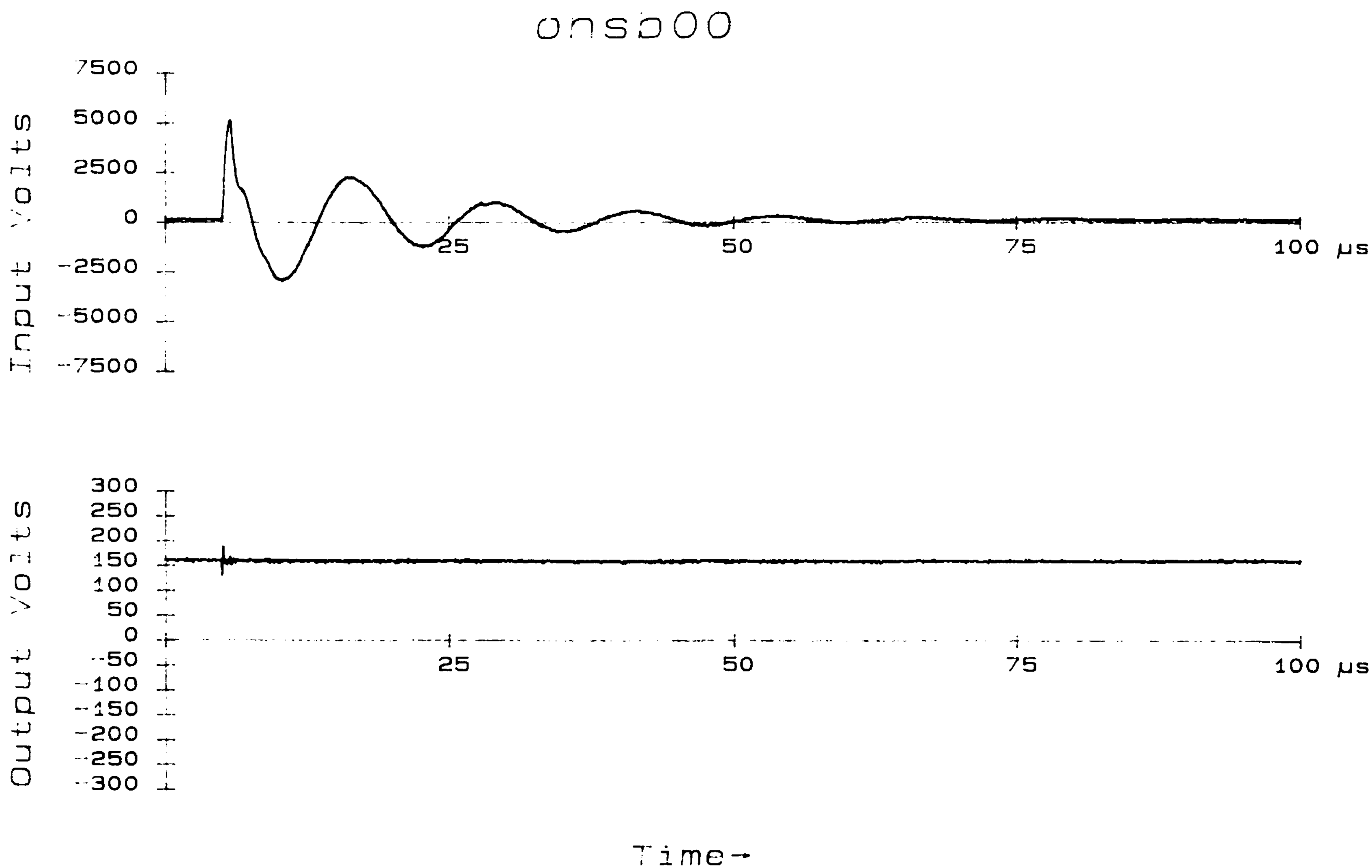


Figure 82. Common-mode ring wave test of a Oneac device with a 35 Ω load.

measurements, but they have a peak rating of only 500 V, which was less than anticipated in many of these experiments. Each P6055 probe was compensated in the usual way with a 4 V peak-to-peak square wave from a Tektronix model 7854 oscilloscope mainframe. Then both probes were connected to the same signal, the 7A13 amplifier was set to the difference function, and the compensation of the probe was adjusted to give the minimum amplitude at the output of the 7A13. We were able to obtain a common-mode rejection ratio (CMRR) of -48 dB at the edge of the square wave with a sweep rate of 2 μs/div.

The manufacturer's specification for risetime of the P6015 and P6055 probes and 7A13 amplifiers can be used to determine the bandwidth of the probe-amplifier system. The system bandwidth with P6015 probes is 60 MHz and is 52 MHz with the P6055 probes. While this may seem small, the maximum sampling rate of the digitizer provides only 3 samples per cycle of a 60 MHz waveform. Thus the probe bandwidth is compatible with the digitizer's maximum sampling rate. To make wider bandwidth measurements, either custom probes need to be obtained or the work needs to be done in a 50 Ω environment. Custom probes are very expensive. A 50 Ω environment does not accommodate the line conditioner's input and output cables. Therefore this measurement system provides the widest bandwidth at a reasonable cost.

During all of these tests the digitizer was operated at its maximum rate, 200 samples per microsecond.

The differential-mode test circuit is shown in Fig. 83. The overvoltage is coupled from the Keytek generator to the power line at the input of the device under test through series metal oxide varistors (MOVs). These MOVs conduct during the transient, but prevent the 60 Hz sinusoidal waveform from entering the Keytek generator. Because these MOVs must be nonconducting immediately after the transient has ended, it is critical that the MOV conduction voltage be much greater than the peak voltage of the 60 Hz sinusoidal waveform from the mains. The transient generator can provide

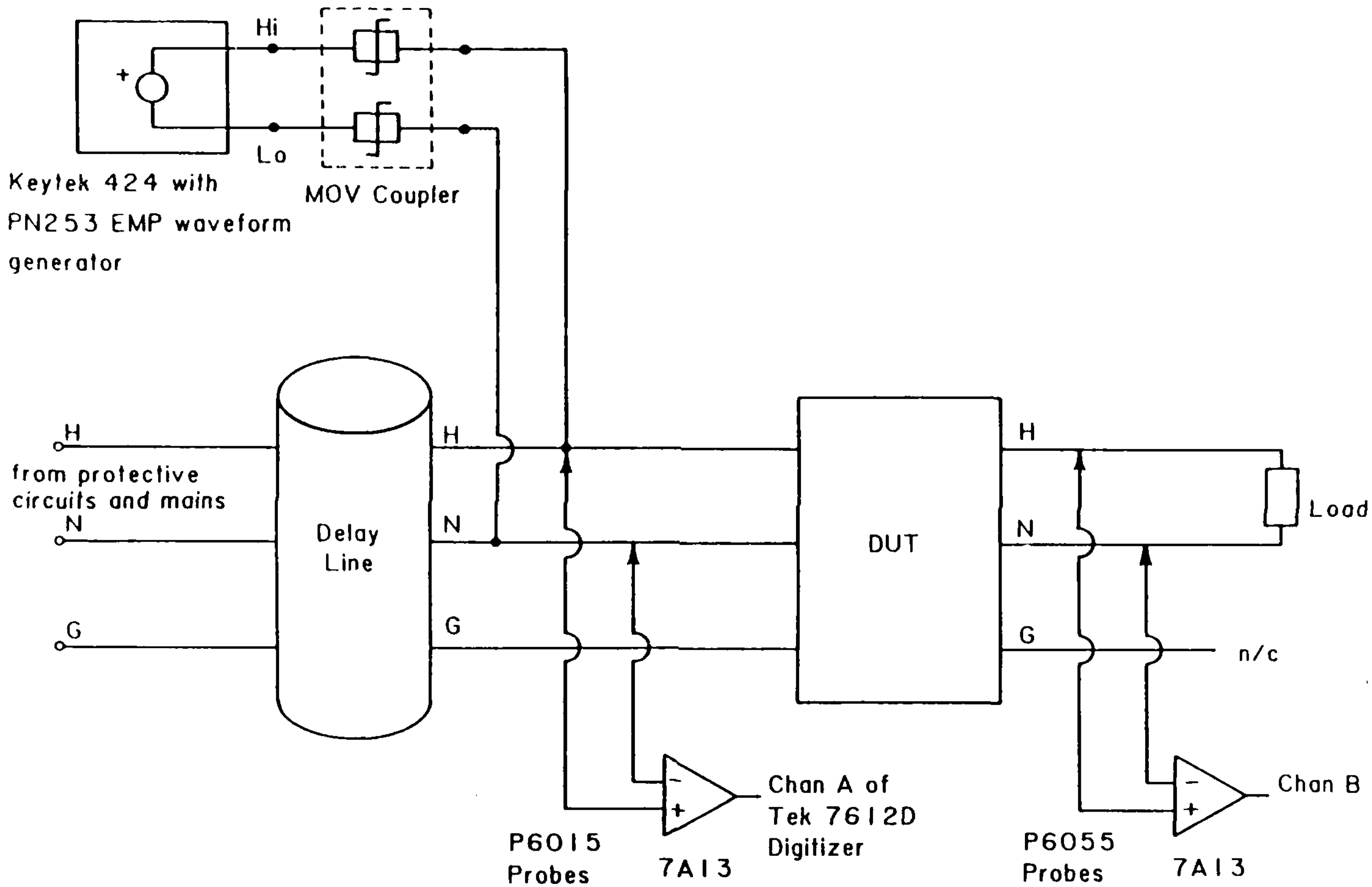


Figure 83. Differential-mode "EMP waveform" tests.

considerable energy to the MOVs that couple the transient to the circuit. For this project MOVs of 32 mm diameter for service on 220 V rms mains were chosen (General Electric part number V250HE250). These MOVs have a maximum energy absorption rating of 220 joules and a maximum peak current rating of 20 kA, both of which are substantially larger than those encountered in these tests. An MOV with a smaller conduction voltage, but with a diameter of at least 32 mm, may have been suitable. We did not wish to risk damaging the transient generator by using an MOV with a smaller conduction voltage.

To protect the instruments in this test, which were powered by the mains, and other electronic equipment in the building, several varistors, inductors, and filters were used. These are shown in Fig. 84.

The inductors prevent the high-frequency (brief risetime) part of the transient from being conducted through the varistors. These inductors are part of the circuit that isolates the experiment from the protective circuit. The protective circuit contains two commercial low-pass filters, each of which attenuates both common-mode and differential-mode signals by at least 30 dB from 0.15 MHz to about 30 MHz when in a 50 Ω test fixture. Several MOVs are used. To provide coordination among the MOVs, those with greater conduction voltages are located nearer the source of the transient. Notice that the varistors are connected to protect against common-mode transient overvoltages, as well as differential-mode transients. Probably not all of these protective devices are required, but redundant and excessive protection is much less expensive than repair of damaged equipment.

The protective circuit alone would compromise the experiment by clamping the input voltage at the device under test. This was avoided by interposing 300 m of 12 AWG three-wire cable between the device under test and the protective circuit. This cable forms a delay line of about 3 μs round-trip. The delay line and initial inductors prevent the initial MOVs from clamping the input voltage at the device

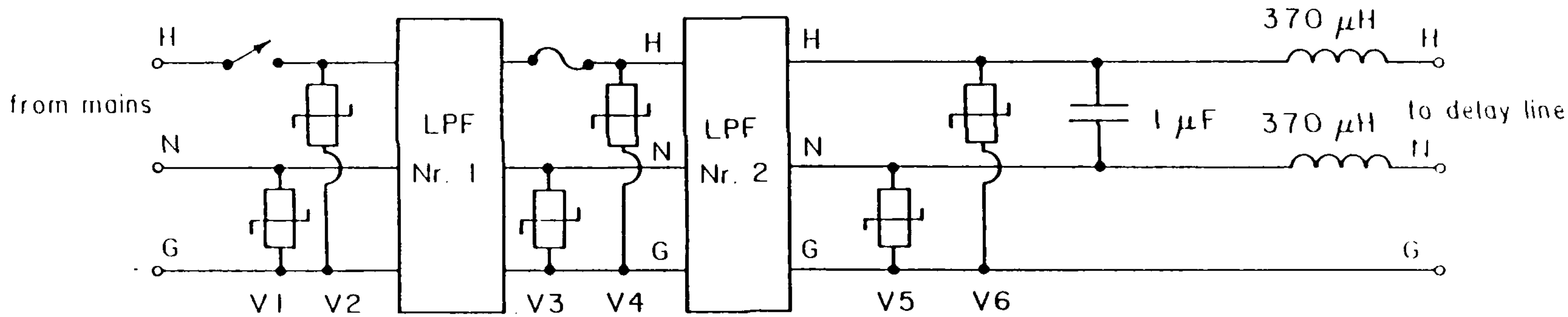


Figure 84. Protective circuit for mains. Metal-oxide varistors V1 and V2 are General Electric Model V150HE150; varistors V3 and V4 are General Electric Model V660PA100C; varistors V5 and V6 are General Electric Models V510HE500. Low pass filter Nr. 1 is Corcom model 20V1; filter Nr. 2 is Corcom model 10SP1A.

under test. Thus the delay line and initial inductors form a network that isolates the protection circuit from the experiment. The delay line has a characteristic impedance of 117 Ω, which appears in parallel with the equipment under test.

When the transient occurs, part of it enters the delay line and travels toward the protective circuit; the remainder of the transient current enters the input terminals of the device under test. The leading edge of the transient is reflected from the initial inductors (and initial MOVs), travels back down the delay line, and arrives at the device under test about 3 μs after the transient began.

These transients were applied at random phase angles of the 60 Hz sinusoidal mains voltage, unlike the ring waves, which were applied at 90 or 180 degrees of the sinusoidal mains voltage. All devices were tested with a 35 Ω load; then the tests were repeated with a 15 μF capacitive load.

All devices that were tested exhibited ringing at about 20 MHz for at least 0.5 μs after the leading edge of the transient. The three line conditioners and Oneac unit had output voltages between 65 V peak to peak and 100 V peak to peak during these transients when a 35 Ω load was connected to the device under test. The Sola ferroresonant line conditioner had a 100 V peak-to-peak excursion at the output, as shown in Fig. 85 (file SOWB00). The Oneac unit had the smallest transients at the output; the data are shown in Fig. 86 (file ONWB00).

The transients at the output could be greatly attenuated by connecting three metal-oxide varistors (MOVs) upstream from the line conditioner, as shown in Section 3. When this was done, the output voltage of the ferroresonant transformer was reduced to 68 V peak to peak, as shown in Fig. 87 (file SOWB01). The output voltage of the Topaz tap-switching conditioner with MOVs upstream was 13 V peak to peak.

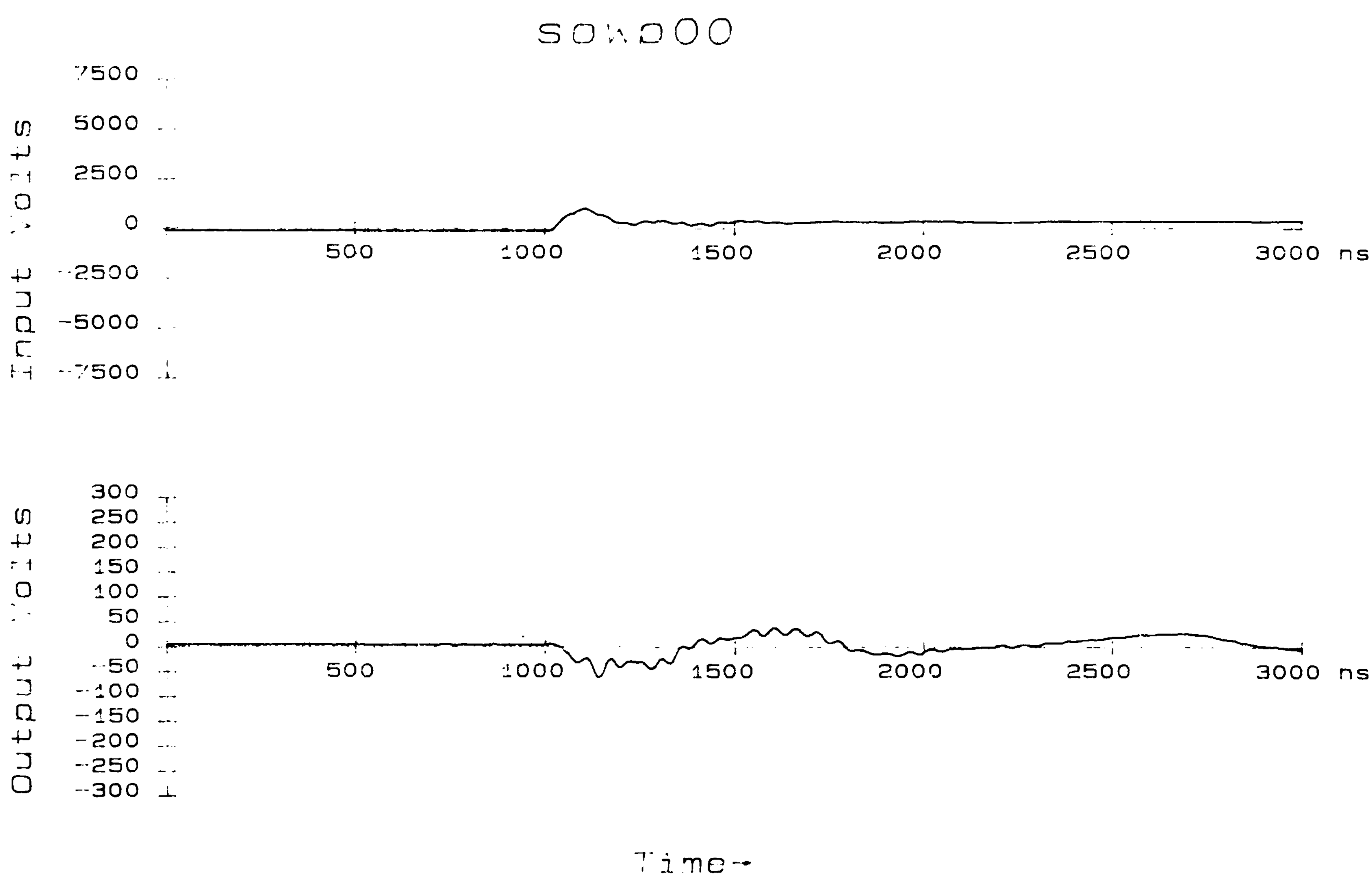


Figure 85. Differential-mode "EMP waveform" test of Sola ferroresonant conditioner with a 35 Ω load.

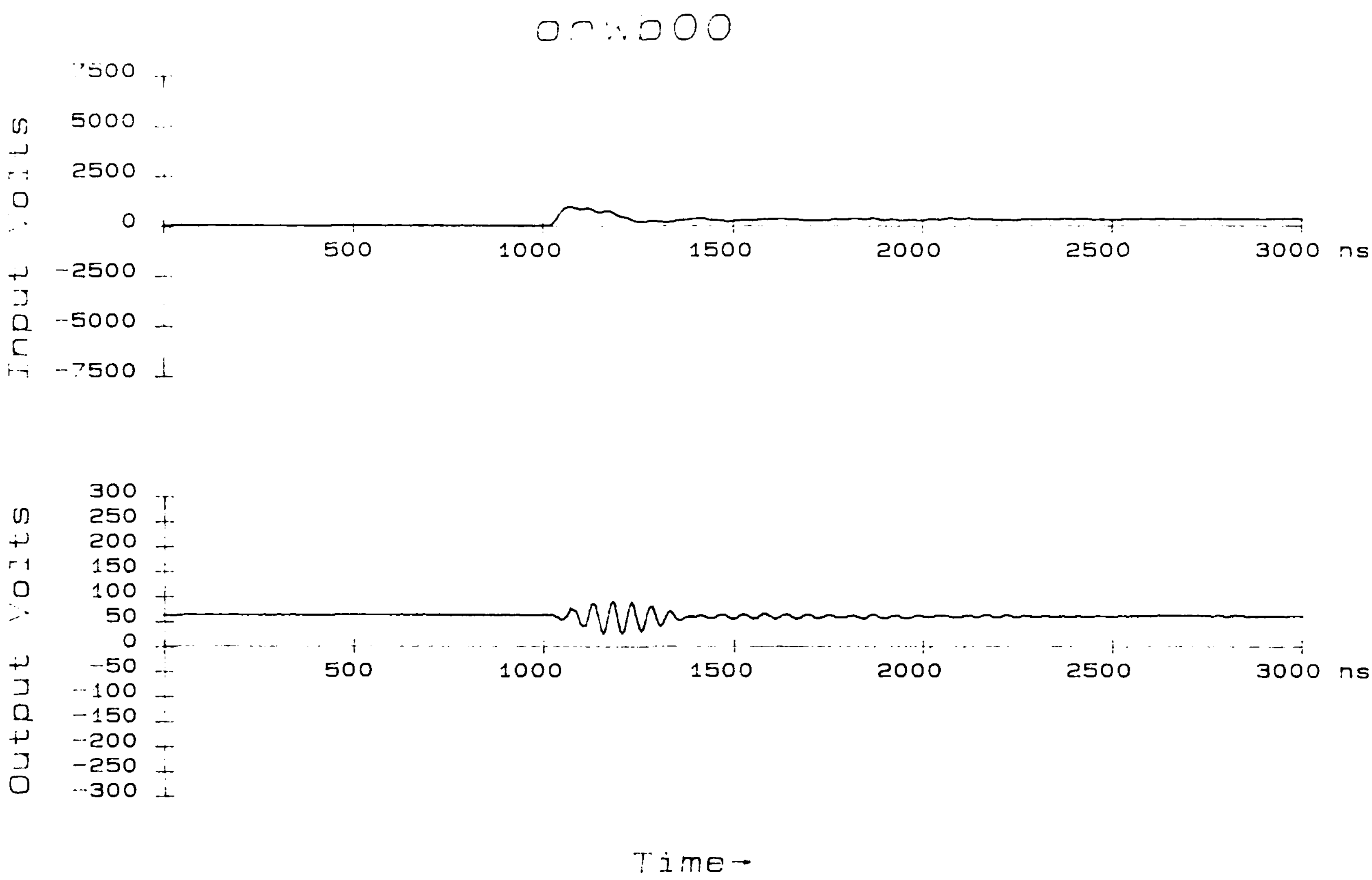


Figure 86. Differential-mode "EMP waveform" test of Oneac device with a 35 Ω load.

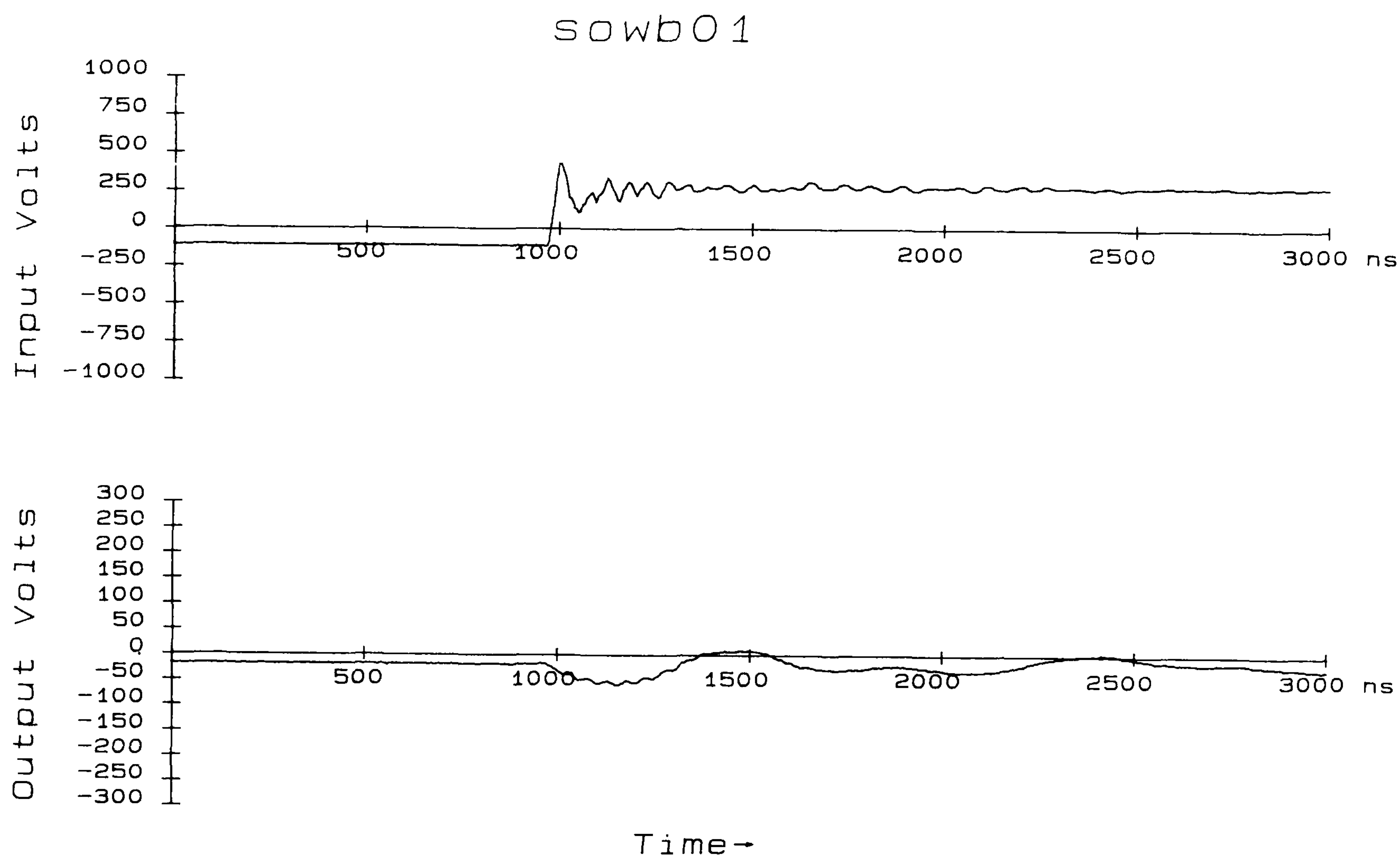


Figure 87. Differential-model EMP test of Sola ferroresonant conditioner with metal oxide varistors upstream and a 35 Ω load.

The peak-to-peak output voltage was always less when a 15 μF capacitive load was used than when a 35 Ω resistive load was used. Apparently the capacitor formed part of a low-pass filter with the series impedance of the line conditioner.

These tests were repeated with common-mode stresses. The test circuit is shown in Fig. 88. The three line conditioners and Oneac unit had output voltages between 70 V peak to peak and more than 100 V peak to peak. The Deltec tap-switching line conditioner had the smallest peak-to-peak output voltages, shown in Fig. 89 (file DEXB00).

8x20 μs WAVEFORM TEST METHODS

ANSI Standard C62.41-1980 prescribes a current waveform that is representative of unipolar transients inside buildings near the point of entry of the mains. The current has a 10% to 90% risetime of 6.4 μs and an exponential decay that reaches half of the peak value 20 μs after the beginning of the waveform. This waveform is known as an "8x20 μs" waveform. The 8x20 μs waveform is useful for testing low impedance devices such as metal oxide varistors. It is not clear that it is appropriate to test line conditioners with an 8x20 μs current waveform; however, it was done as an example of response under a different kind of stress than other waveforms discussed previously.

The schematic diagram of the experiment is shown in Fig. 90. This is the only experiment in this research project in which the device under test was not energized when the transient overvoltage was applied. Large transients can be coupled to the mains via series metal oxide varistors, as described above for the EMP waveform. The varistors used for coupling should have a conduction voltage that is much larger than the peak of the mains voltage. This choice prevents thermal runaway of the varistor after severe transients. In this research project varistors with V_N of about 400 V (see Section 3 for definition of V_N) were used. Since the peak open-circuit voltage of the 8x20 μs waveform generator was only about 1 kV, a transient of only about 200 V could be applied to the device under test in the

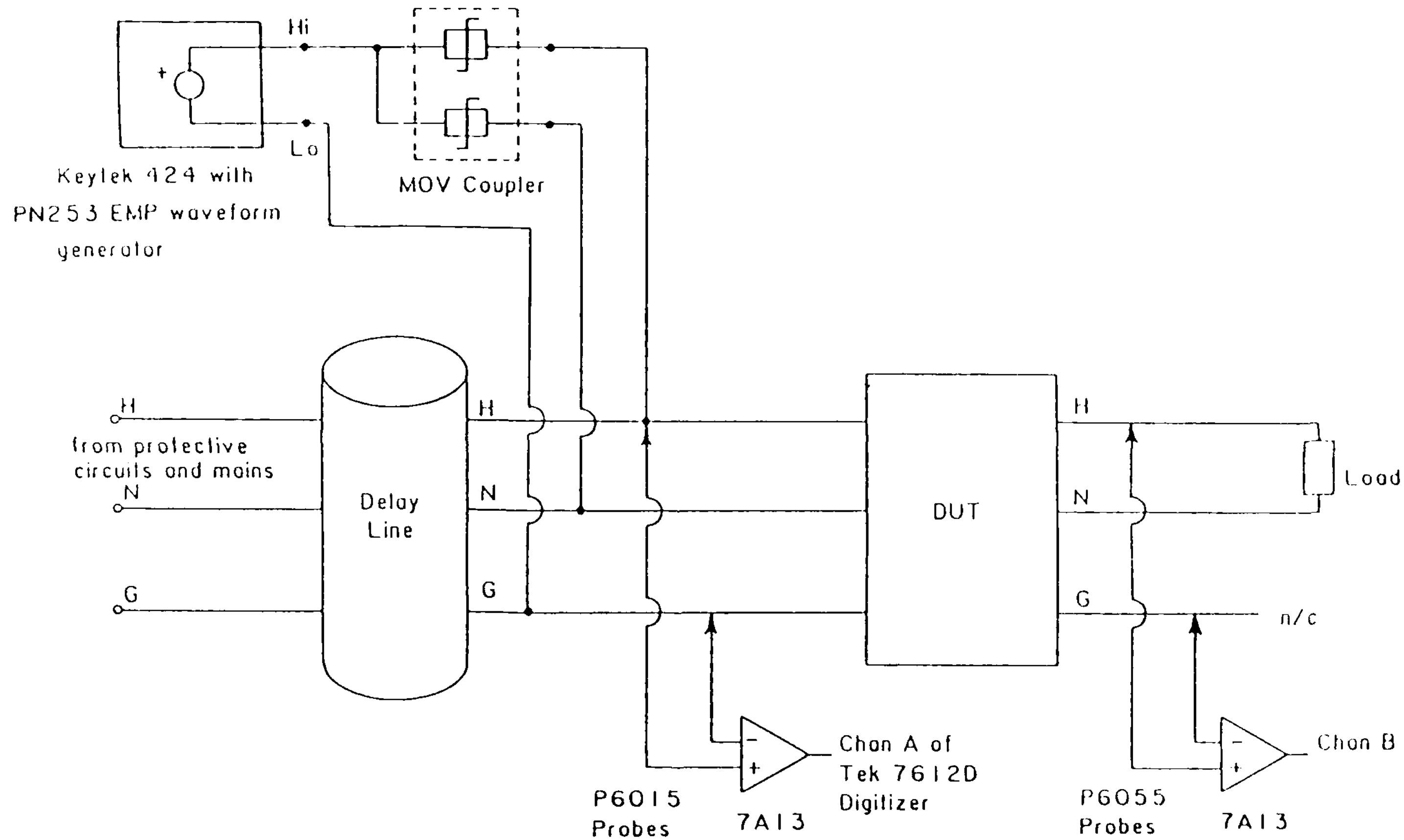


Figure 88. Common-mode "EMP waveform" tests.

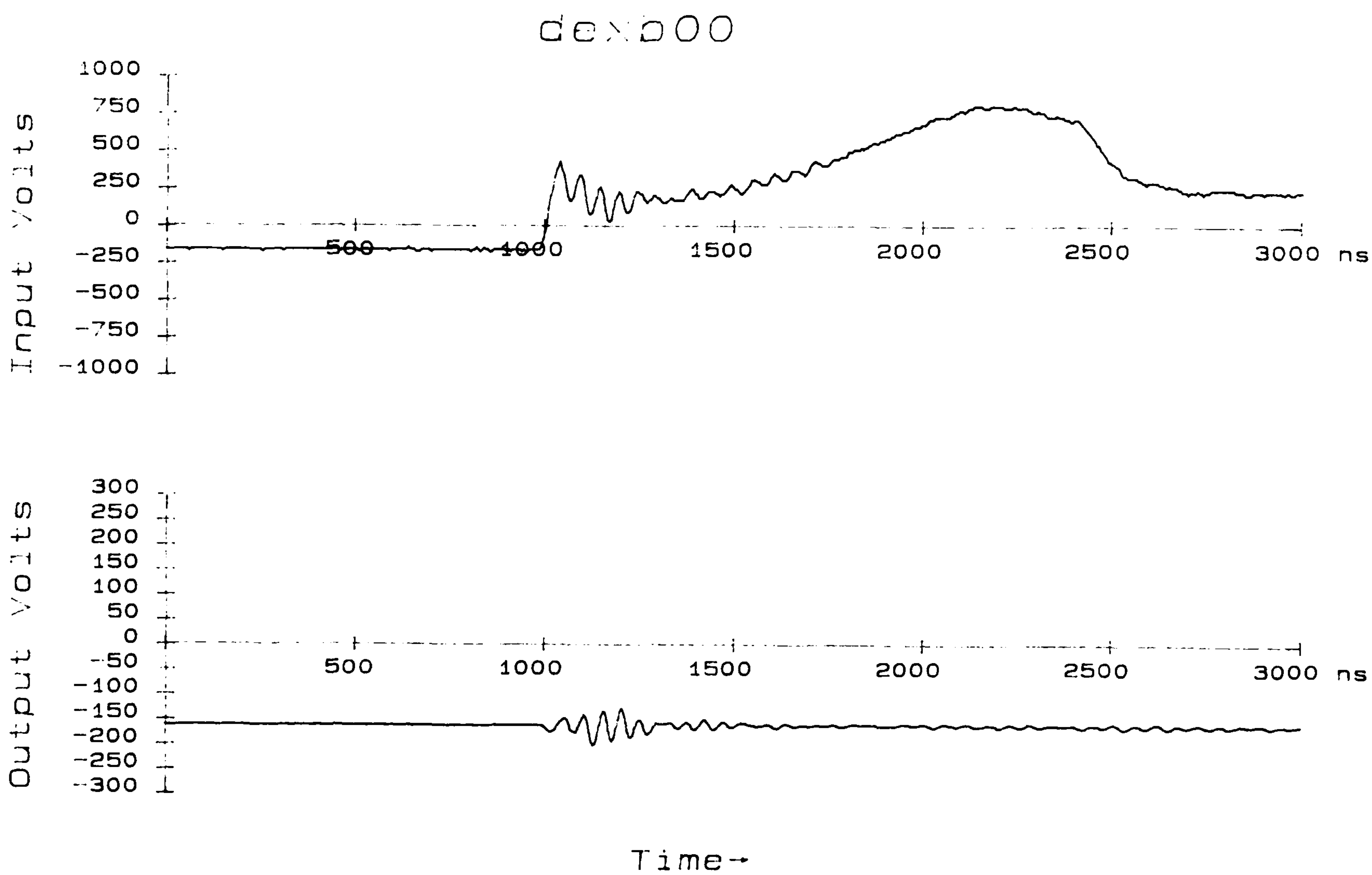


Figure 89. Common-mode "EMP waveform" test of Deltec tap-switching conditioner with a 35 Ω load.

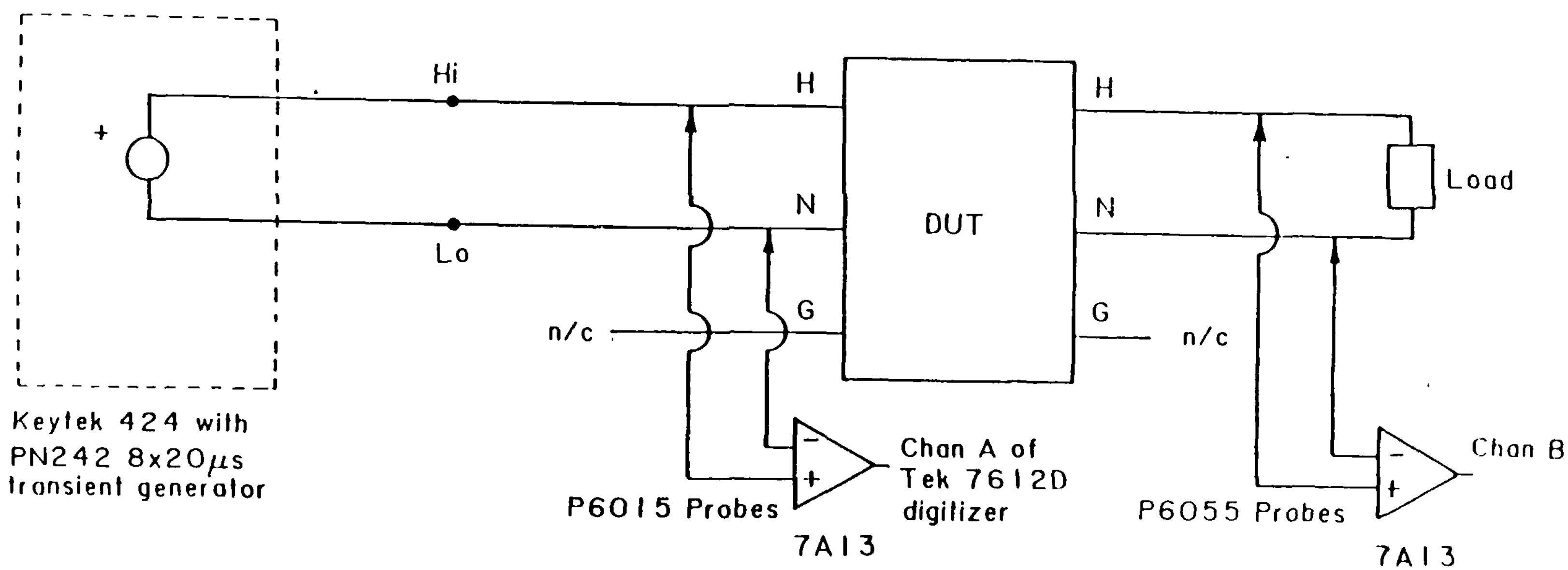


Figure 90. Differential-mode 8x20 μs wave tests.

differential-mode. Since the series varistors reduced the transient voltage to a small value, it was decided to apply the 8x20 μs waveform directly to the input of the device under test without any connection to the mains.

The 8x20 μs waveform was provided by a Keytek Model 424 generator with a PN 242 plug-in. The 500 A peak short-circuit current and a 1 kV peak open-circuit voltage were used. These were the maximum current and voltage available from the PN242 waveshaping plug-in unit.

The voltage probes and amplifiers were identical to those described above in the EMP waveform section.

The 8x20 μs waveform tests were applied to each device under test with a 35 Ω resistive load. The tests were repeated with a 15 μF capacitive load. All tests were done with both differential- and common-mode transients at the input.

8x20 μs WAVEFORM TEST RESULTS

The Sola ferroresonant line conditioner had a peak output voltage of 120 V during a 530 V peak differential-mode stress at the input. The peak output voltage was less than 3 V during a 1 kV common-mode stress at the input.

The Topaz tap-switching line conditioner had a peak output voltage of 54 V during a 1 kV peak differential-mode stress at the input. The peak output voltage was less than 3 V during a 1 kV common-mode stress at the input.

The most interesting results of the 8x20 μs waveform tests occurred with the Deltec tap-switching line conditioner. Results from a differential mode test are shown in Fig. 91 (file DETB00). The line conditioner did a good job of attenuating the peak input voltage.

The response of the Deltec tap-switching conditioner to a common-mode transient was then measured. The hot and neutral conductors at the input of the line conditioner were connected together. The transient was applied between these conductors and ground as shown in Fig. 92. A loud noise was emitted by the Deltec tap-switching line conditioner during this common-mode test. The test data are shown in Fig. 93 (file DEUB01). The line conditioner was disassembled, and an 0.02 μF capacitor with a ceramic dielectric was found to have exploded. About half of the capacitor body remained in the circuit between line and ground, and burn marks were observed at the edge of the break. The failed capacitor was marked with a "1 kV" voltage rating, which was certainly exceeded during these tests. It is possible that the capacitor failed as a result of mechanical stress caused by the piezoelectric effect in the dielectric during the pulse test. Alternately, it may have failed by dielectric breakdown. The subsequent arc could have vaporized material and exploded the capacitor. The sudden decrease of input voltage at 11.3 μs in Fig. DEUB01 probably represents the crowbar action when an arc formed across the capacitor. This capacitor is part of an LC low-pass filter circuit. The inductor upstream prevented the input from being shorted, which explains why the input voltage did not drop to zero.

The electrostatic shield inside the Deltec line conditioner should block common-mode signals. This probably explains why the output voltage was zero during all of Fig. 93 (file DEUB01).

The peak output voltage of the Oneac unit was about 190 V for a peak input of 800 V differential-mode. The output of the Oneac unit during a 1 kV common-mode stress had a peak of only 3 V. Again, MOVs upstream from the device would attenuate output voltages that were observed with differential-mode transients at the input of all of the line conditioners that were tested.

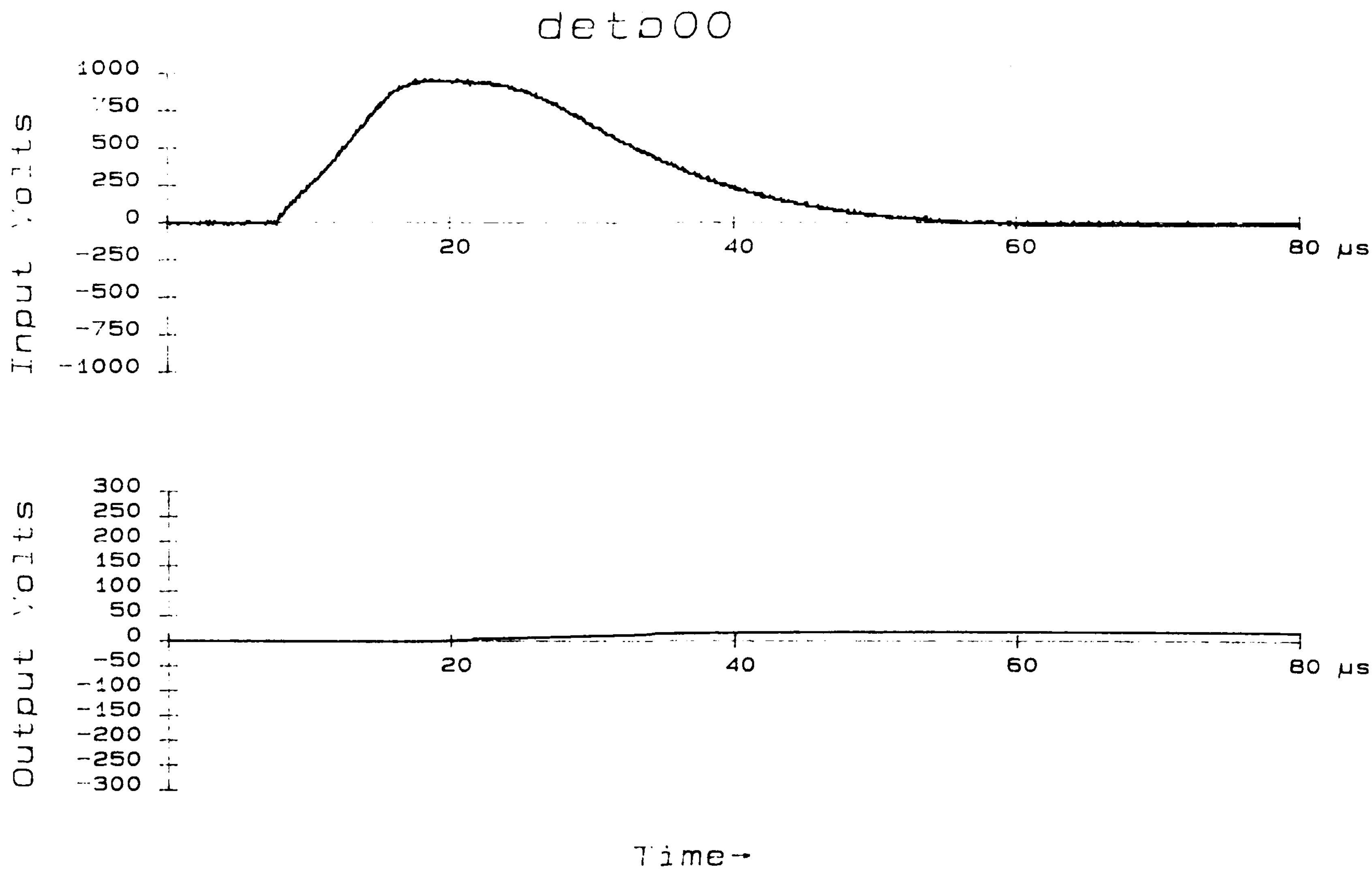


Figure 91. Differential-mode 8x20 μs waveform test of Deltec tap-switching conditioner with a 35 Ω load.

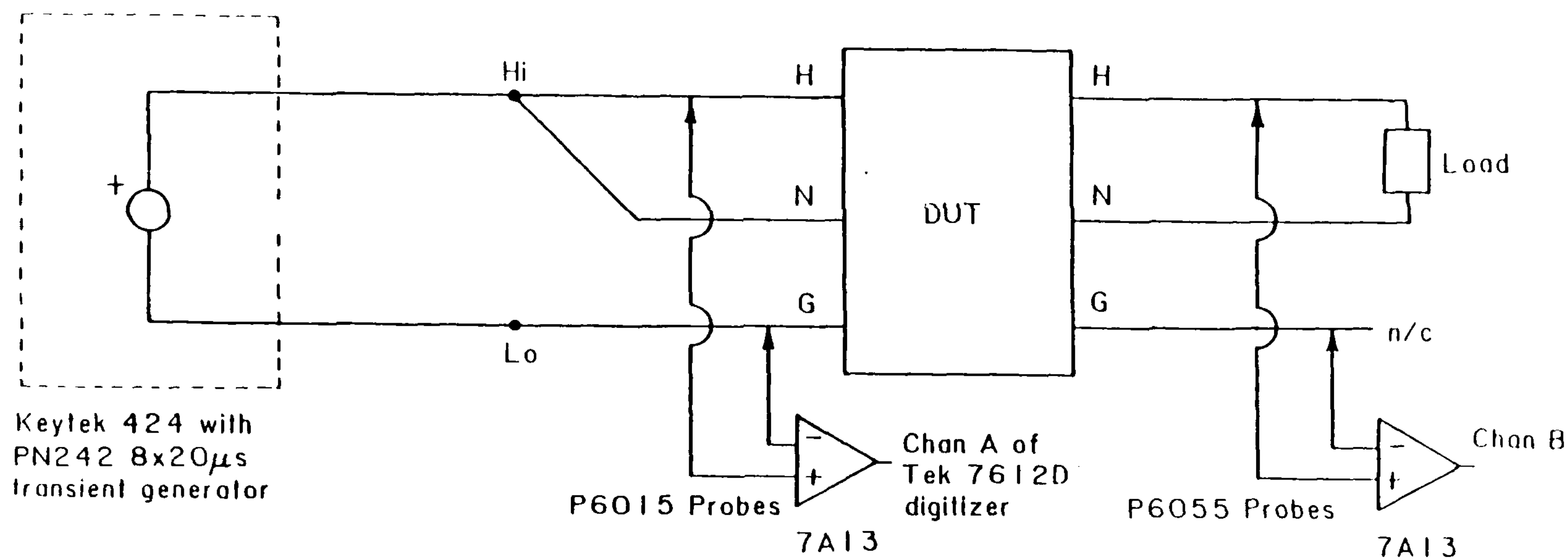


Figure 92. Common-mode 8x20 μs wave test.

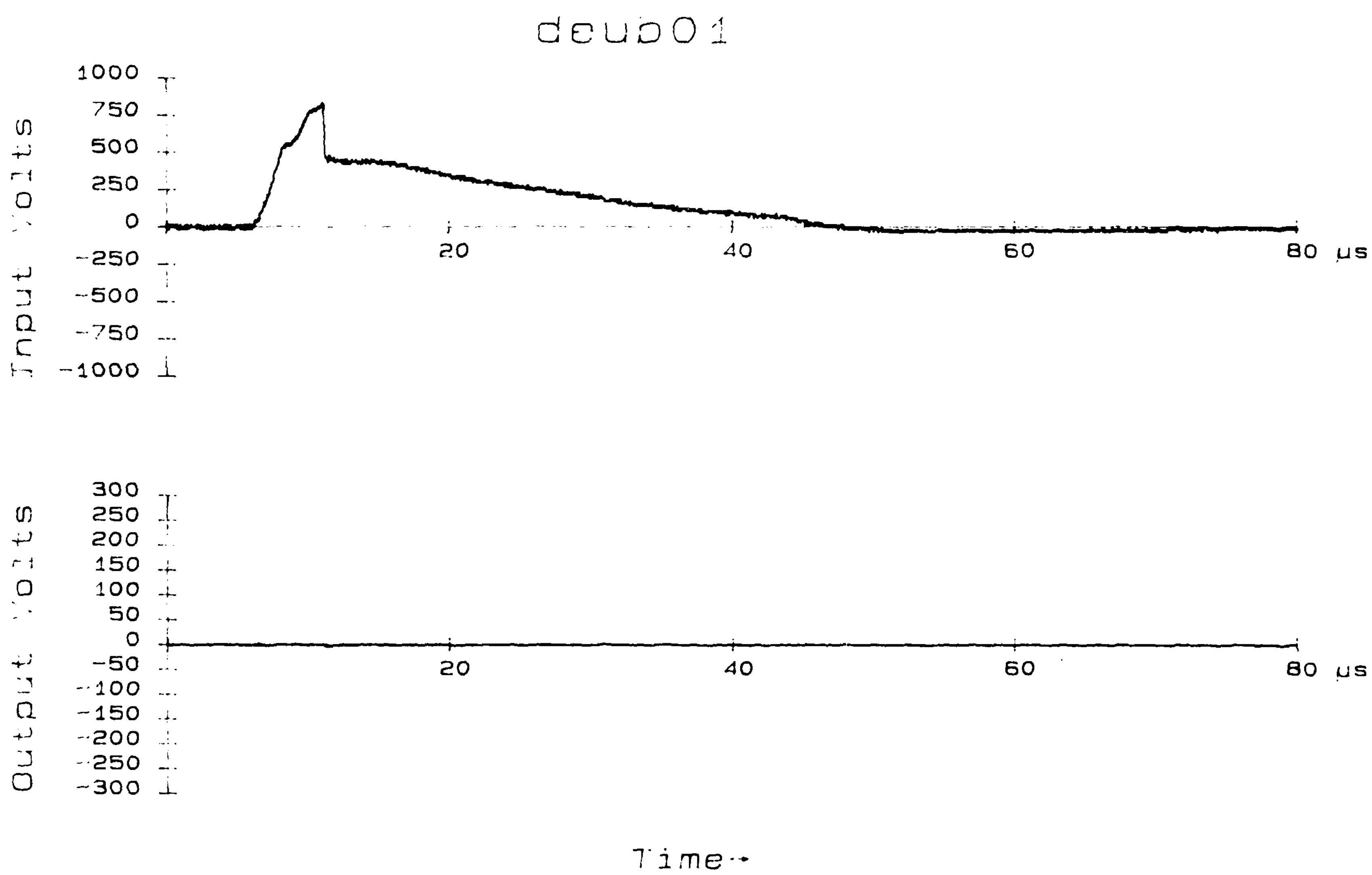


Figure 93. Common-mode 8x20 μs test of a Deltec tap-switching conditioner with a 35 Ω load. The conditioner was damaged during this test.

LARGE PULSE TESTS

The final set of measurements was performed with a custom transient generator that was designed and constructed by one of us (RS). This transient generator was designed to satisfy three criteria:

1. peak short-circuit current greater than 10 kA,
2. risetime as small as possible,
3. peak open-circuit voltage adjustable between 2 kV and 6 kV.

No attempt was made to provide a specific waveshape. A plot of this transient generator's output voltage with a 35 Ω load is shown in Fig. 94 (file XXYB00). The peak voltage of 5 kV is attained about 0.15 μs after the beginning of the transient. The initial part of the waveform has a slope of 400 kV/μs. These data may be limited by the 6 ns risetime of the combination of the P6015 probes and 7A13 amplifier as well as the 5 ns sample interval of the digitizer. Ringing of the output voltage in Fig. 94 (file XXYB00) may be due to the parasitic inductance and capacitance in the test fixture and pulse generator.

This transient generator was connected to the line conditioner under test with the circuit shown in Fig. 95. The MOV coupler, delay line, and protective circuits were all discussed above in the "EMP Waveform" section. Inductors with a ferrite core and special high voltage design were connected between the test fixture and delay line. These inductors prevent the leading edge of the transient from entering the delay line. Without these inductors the delay line would be connected in parallel with the device under test.

As in the "EMP Waveform" tests, the phase of the 60 Hz sinusoidal waveform was random when the transient was applied.

Differential-mode test results for the Sola ferroresonant line conditioner are shown in Fig. 96 (file SOYB01). The 60 Hz output voltage was about 115 V when the transient was applied 0.6 μs after

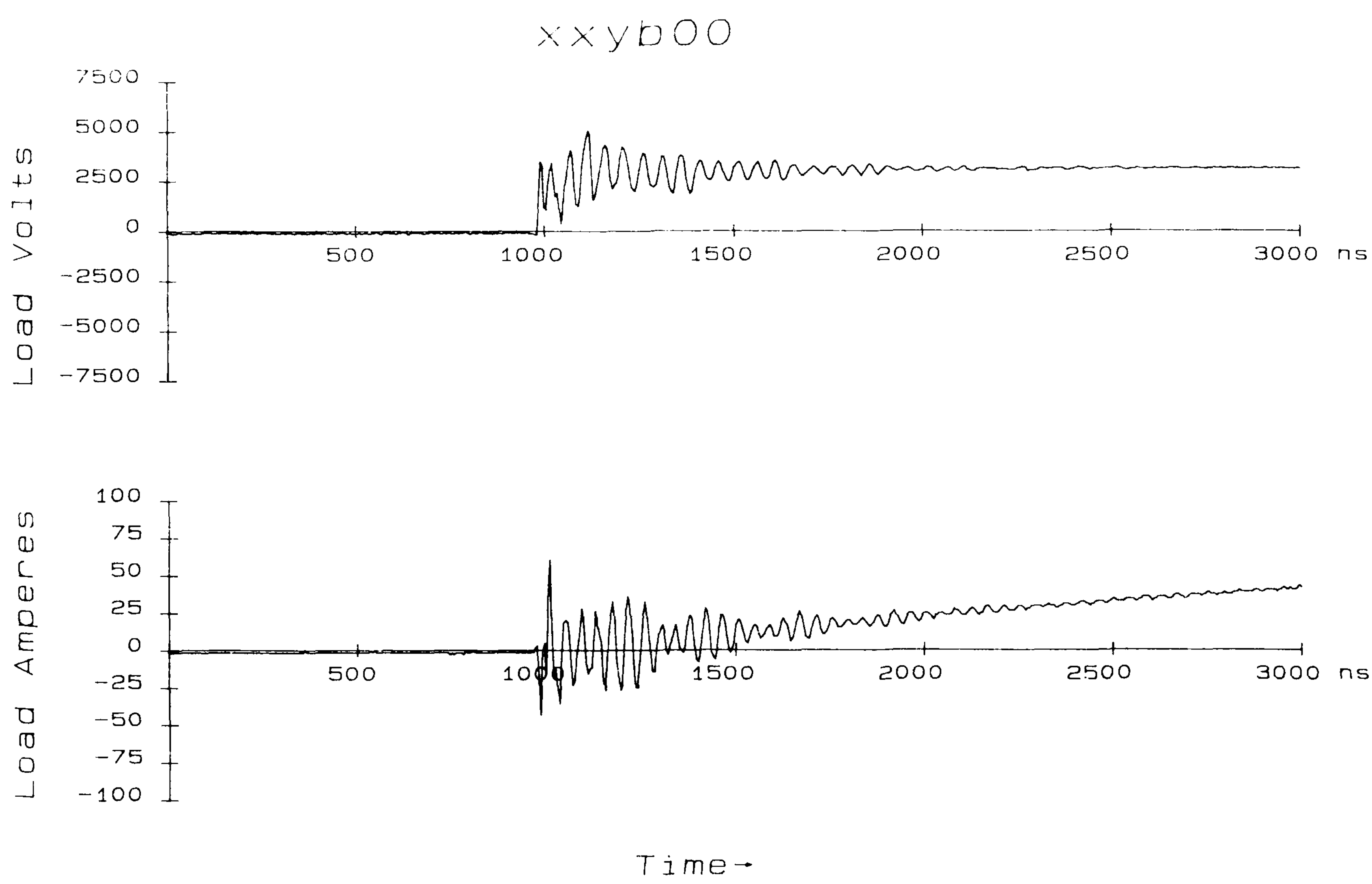


Figure 94. Differential-mode large pulse generator output with a 35 Ω load.

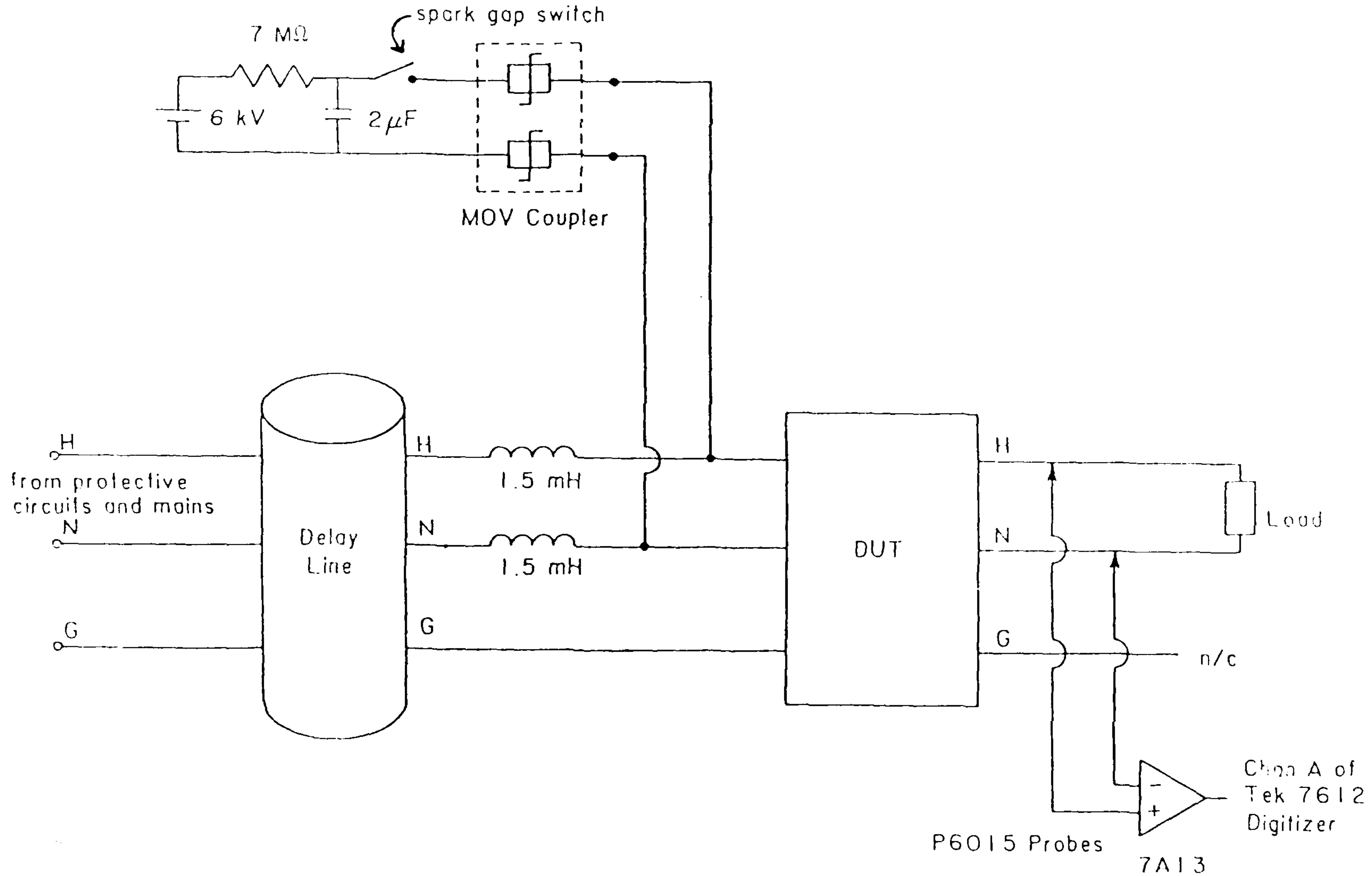


Figure 95. Differential-mode large pulse tests.

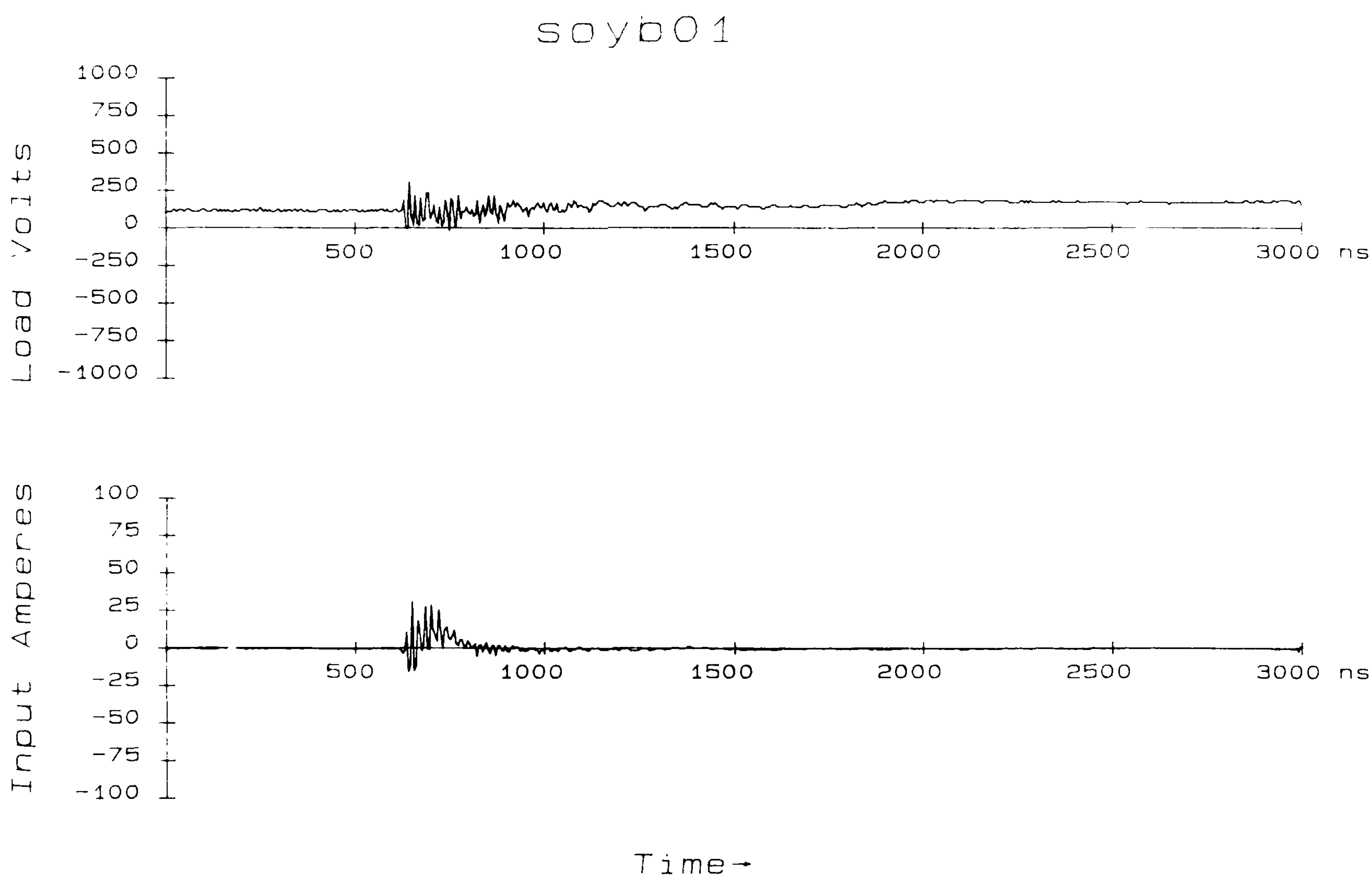


Figure 96. Differential-mode large pulse test of a Sola ferroresonant conditioner with a 35 Ω load.

the record began. The output voltage of the ferroresonant line conditioner shows a 330 V peak-to-peak excursion, with a peak of about 310 V. Only the first 3 μs of the record is shown in Fig. 96 and others that follow, although data were taken for a 10 μs interval at 5 ns per sample. Showing only the first part of the record avoids showing reflections from the protection circuit in Fig. 84 and gives better time resolution in the figures. The largest voltage excursions on the output of the conditioners in each record always occurred during the first 3 μs of the record and are shown in this report.

Differential-mode test results for the Topaz tap-switching line conditioner are shown in Fig. 97 (file TOYB03). The record in Fig. 97 was obtained at a much slower sample rate than that of Fig. 96 (file SOYB01). The transient was applied 20 μs after the record in Fig. 97 begins, when the mains voltage was about 100 V. The peak output voltage of the line conditioner was about 750 V when the data were smoothed to remove quantization noise in the digitizer.

The Deltec line conditioner could not be tested because it was damaged by the 8x20 μs tests.

The common-mode test circuit is shown in Fig. 98. There are three changes from the differential-mode test circuit. The transient was coupled to the device under test differently. The two probes that were connected to the inverting inputs were moved from neutral to ground.

The output voltage of the Sola ferroresonant line conditioner during a common-mode transient is shown in Fig. 99 (file SOZB01). The transient was applied 0.46 μs after the beginning of the record, when the 60-Hz output voltage was about 165 V. The output voltage of the Sola showed a 1340 V peak-to-peak excursion, with a peak of 720 V.

The output voltage of the Topaz tap-switching line conditioner during a common-mode transient is shown in Fig. 100 (file TOZB02). The transient was applied 0.44 μs after the beginning of the record,

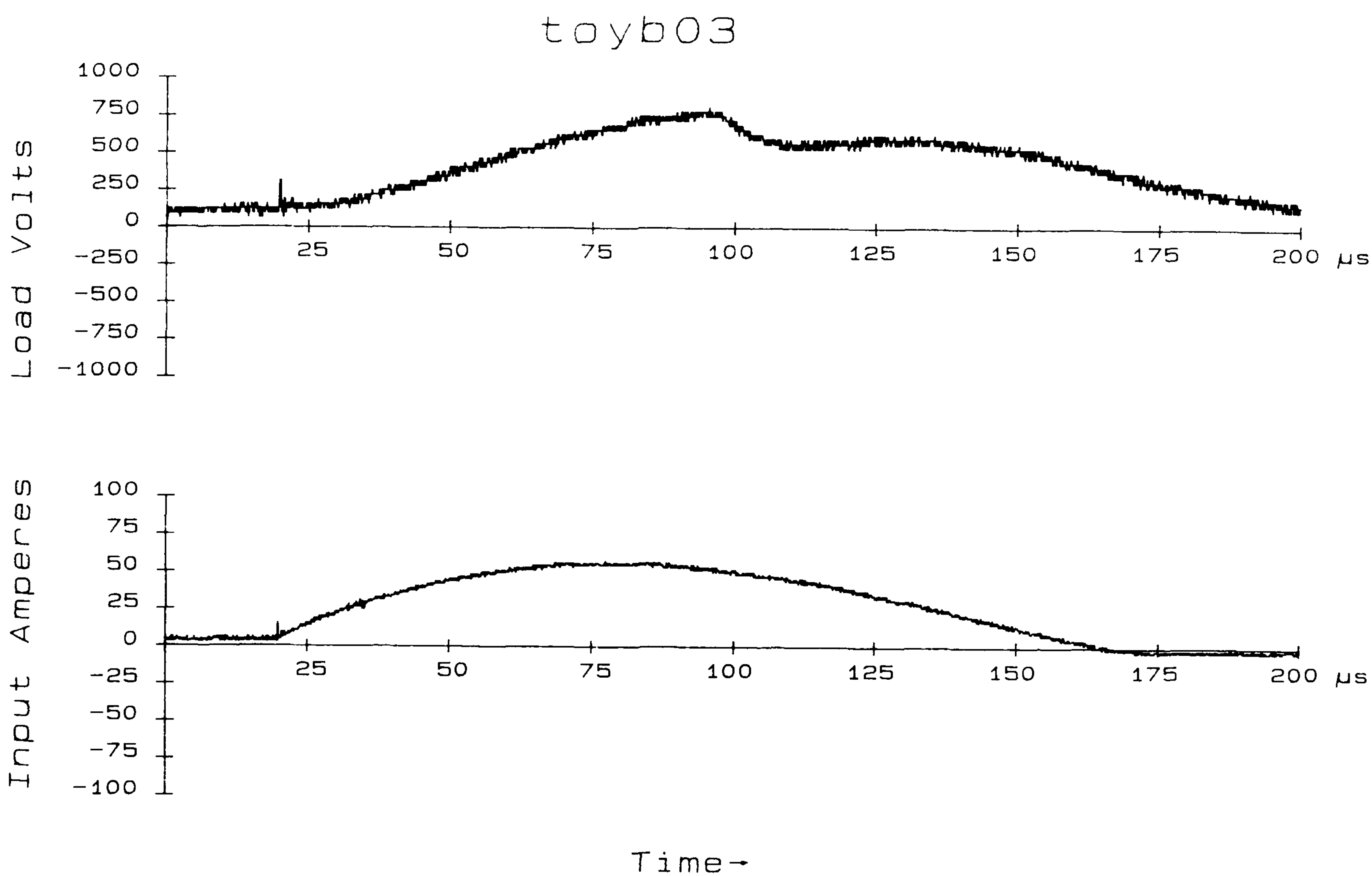


Figure 97. Differential-mode large pulse test of a Topaz tap-switching conditioner with a 35 Ω load.

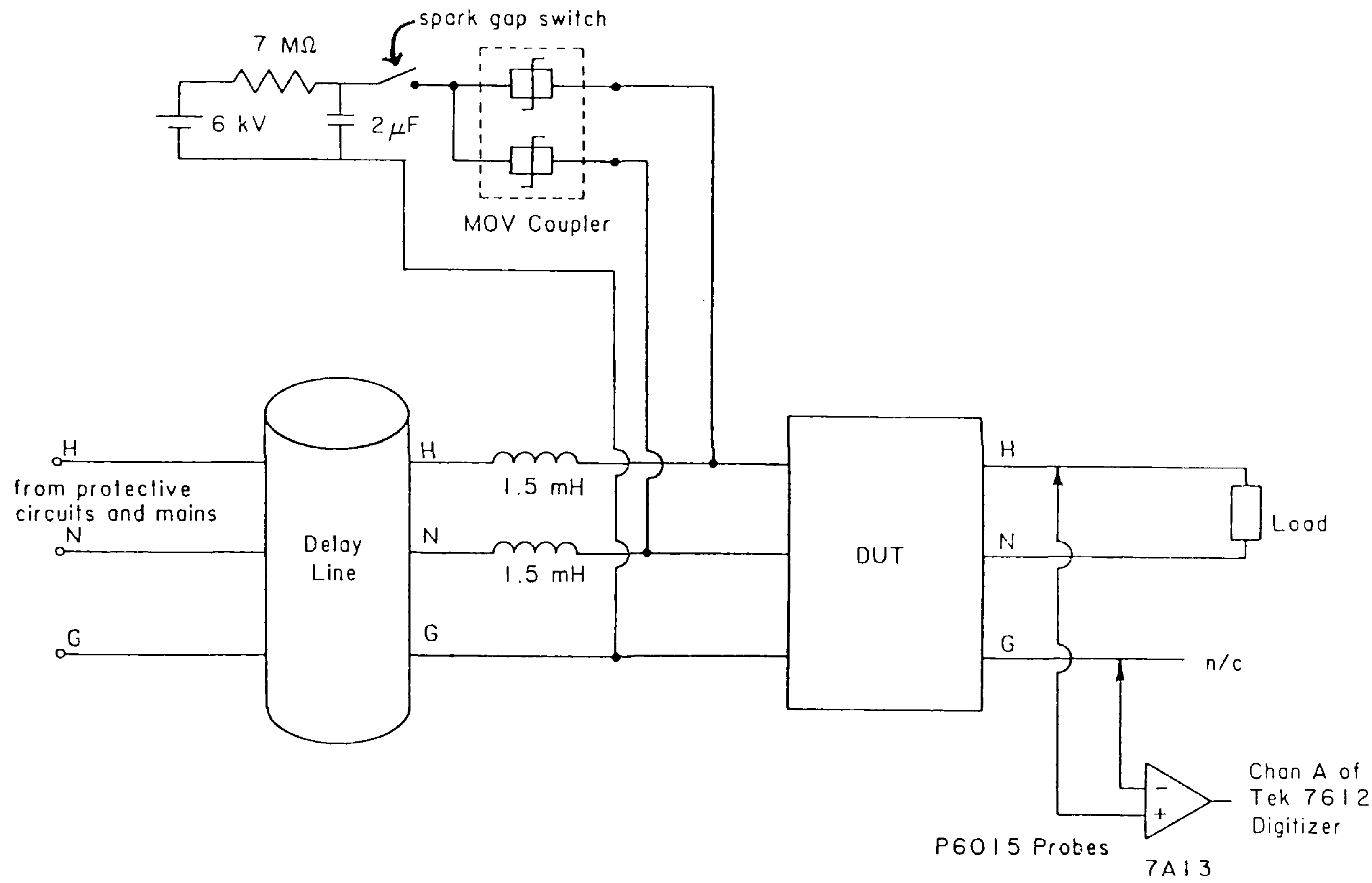


Figure 98. Common-mode large pulse tests.

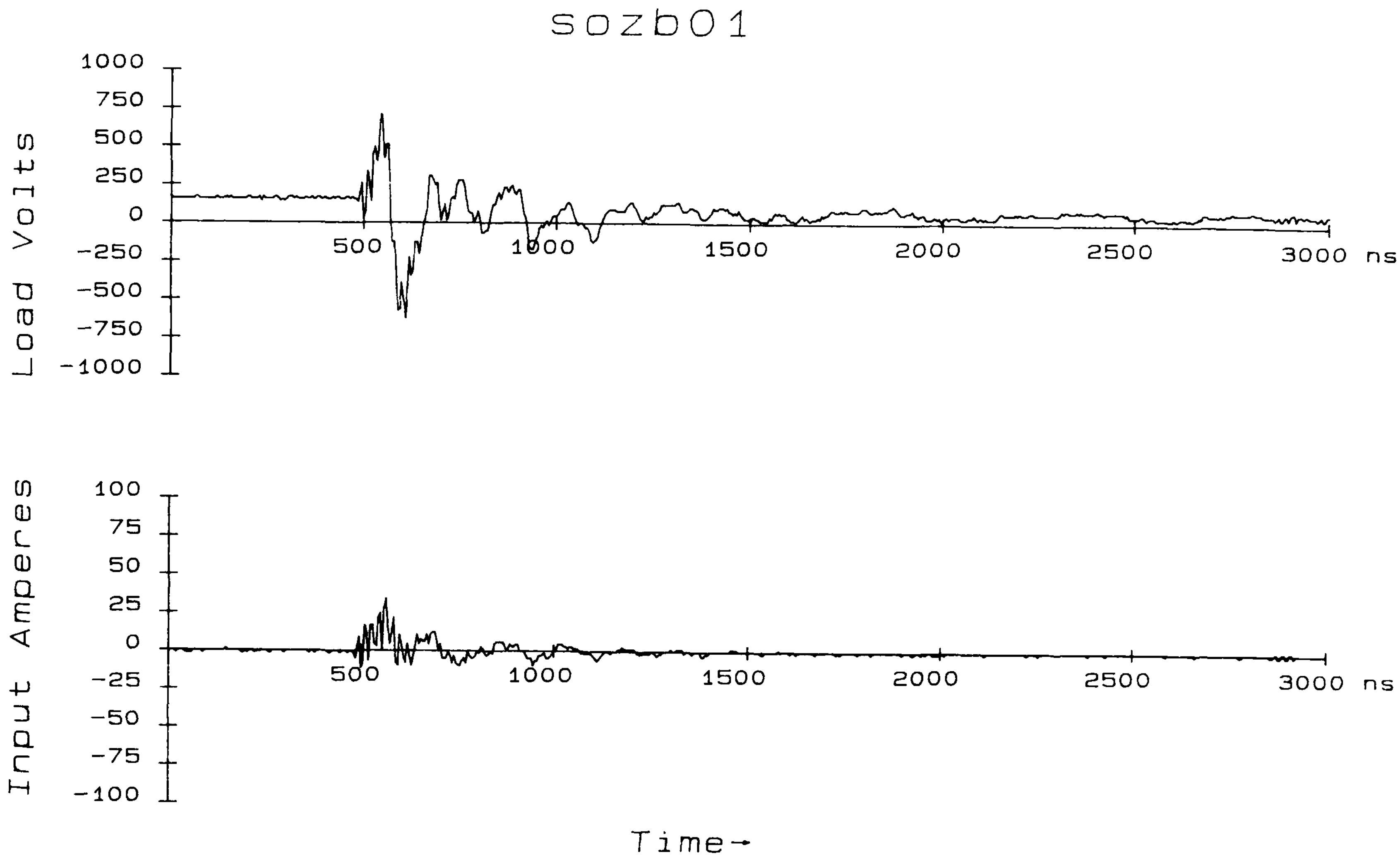


Figure 99. Common-mode large pulse test of a Sola ferroresonant conditioner with a 35 Ω load.

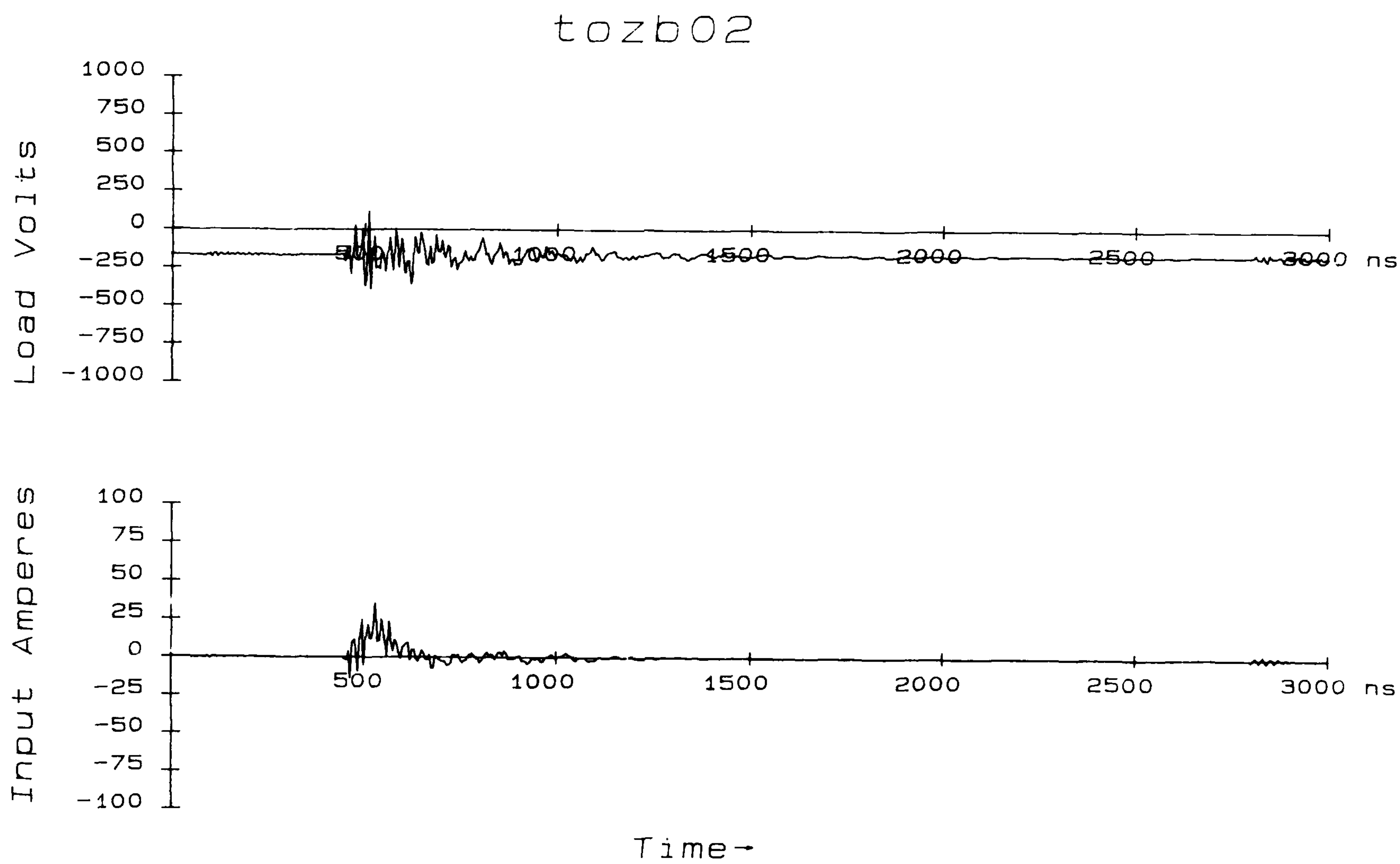


Figure 100. Common-mode large pulse test of a Topaz tap-switching conditioner with a 35 Ω load.

when the 60 Hz mains voltage was about -165 V. The output voltage showed a 520 V peak-to-peak excursion, with a peak of -395 V.

Both the Sola and Topaz line conditioners have large output voltage excursions when this severe transient is applied to the input in either differential- or common-mode. These output voltage excursions could be greatly attenuated by connecting MOVs upstream from the line conditioner.

When three metal-oxide variators were connected to the input cable of the Sola ferroresonant line conditioners, as described in Section 3, the peak output voltages during these pulse tests were reduced. Figure 101 (file SOZB02) shows a peak output voltage of 200 V for a common-mode transient. This should be compared with Fig. 99 (file SOZB01), where no MOVs are used and a peak voltage of 720 V was measured. The authors of this report recommend the use of MOVs, even if line conditioners are used.

After these large pulse tests were completed, the tap-switching circuit in the Topaz line conditioner was found to be nonfunctional. The steady-state output voltage was 150 V rms when the input voltage was about 120 V rms. Apparently the Topaz line conditioner was now permanently connected to respond to a brownout. This failure mode may damage loads that are connected to the line conditioner by overheating the voltage regulator circuit in the power supply of the load. The failure of the tap-switching circuit should not affect the first few microseconds of the output voltage shown in this report because the switching circuit, when functioning, only responds to the time-averaged voltage.

All of the line conditioners and the Oneac device were disassembled, and their internal construction was inspected. One striking finding was the absence of metal oxide varistors inside these devices. The electronic control circuit of the tap-switching line conditioners is vulnerable to damage by transient overvoltages. In

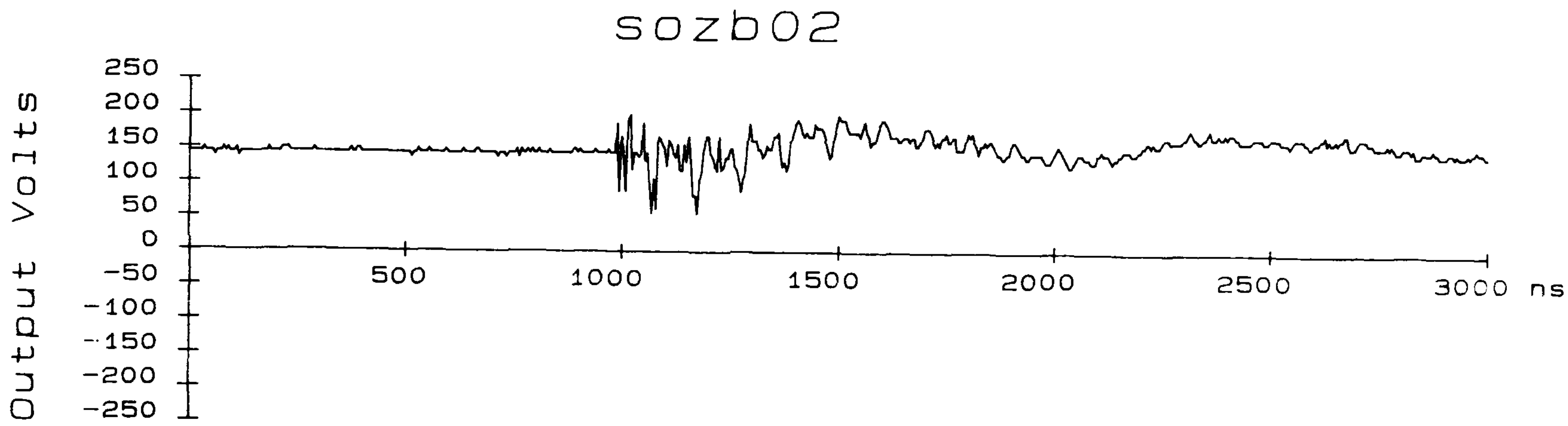


Figure 101. Common-mode large pulse test of a Sola ferroresonant conditioner with a 35 Ω load. MOVs were connected upstream from the conditioner.

fact, both tap-switching line conditioners were damaged during our high voltage pulse tests.

SECTION 8

WHAT IS THE "BEST" KIND OF LINE CONDITIONER ?

As with many other engineering choices, the meaning of "best" depends on the application. There is no easy, universal answer. If the rms load current is appreciably constant <u>and</u> tight regulation of rms voltage at the load is particularly desirable, then a ferroresonant transformer is best, owing to its superior steady-state line regulation properties. If the rms input voltage varies over a wide range (especially if severe brownouts occur) or if there is significant noise on the mains, a ferroresonant transformer is likely to be more satisfactory. For most other applications a tap-switching transformer is preferable. It is smaller, less massive, more efficient, and has better dynamic line and load regulation. Tap-switching transformers are definitely preferable to ferroresonant transformers for loads larger than about 2000 VA.

USE OF LINE CONDITIONER WITH UPS TO PROTECT A COMPUTER SYSTEM

The most attractive way to protect a small computer system from power disturbances is to use a line conditioner with a standby UPS. ("Small" means a power consumption of less than 1000 W.) One must then decide whether to connect the UPS upstream or downstream from the line conditioner. This is not an easy question to answer.

If a ferroresonant line conditioner is chosen for use with a standby UPS, the UPS should probably be located downstream from the ferroresonant line conditioner. This has the following advantages:

1. The ferroresonant line conditioner will then boost the voltage during brownouts and sags so that the UPS is not needed to correct those conditions. This will prevent draining the UPS batteries during prolonged brownouts.
2. During a blackout the relatively inefficient ferroresonant line conditioner will not consume power from the UPS. In

this way longer system operation is possible for a specified UPS capacity.

3. The UPS can then prevent severe sags in voltage at the load due to the poor dynamic load regulation of ferroresonant transformers.

4. The UPS will not need to provide the initial current surge that occurs when a ferroresonant line conditioner is switched on. If the UPS is upstream from the ferroresonant transformer, the circuit breaker in the UPS may trip during this current surge.

If a tap-switching line conditioner is chosen for use with a standby UPS, the relative location of the conditioner and UPS is less important. In order to obtain minimum noise at the load, the UPS should be placed upstream from the tap-switching line conditioner. This also allows the UPS to charge its batteries while the remainder of the system is off. This is a minor consideration if blackouts are infrequent <u>and</u> the system is frequently used (e.g., at least 10 h/wk), so that the UPS can trickle charge its batteries during normal system operation.

TURN-ON AND TURN-OFF SEQUENCE

The user should establish a definite sequence for turn-on and turn-off of a computer system. The proper sequence minimizes voltage fluctuations at the load, as well as establishes proper handshaking between the computer and peripheral devices.

Consider the system shown in Fig. 102. To begin system operation, turn on the line conditioner first. Second, turn on the UPS. Then turn on the master switch on the outlet strip to which the loads are connected (be certain that all loads have their individual switches in the off position). Finally, turn on the various loads, <u>one at a time</u>. The proper sequence for turning on the loads will depend on the system. As a general rule, turn on peripheral devices (e.g., printer, disk drive) <u>before</u> the computer is turned on.

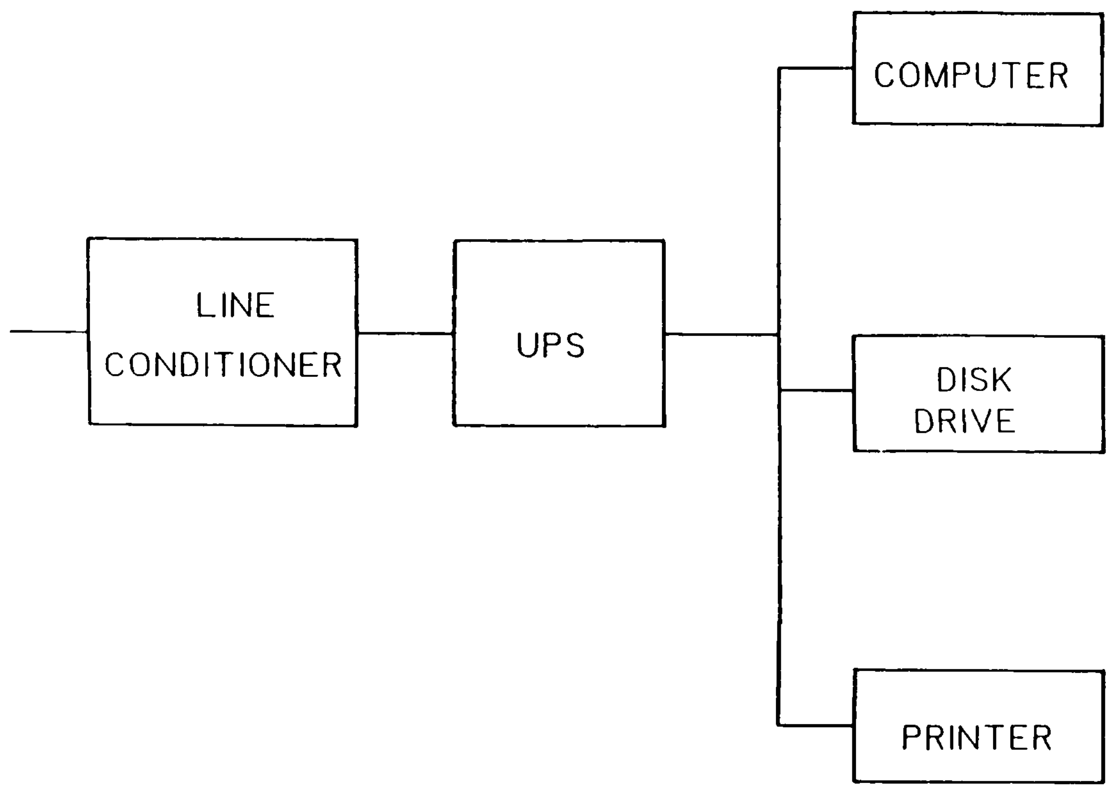


Figure 102. Use of ferroresonant conditioner and standby UPS with computer system.

This sequence minimizes sags in voltage at the load by minimizing the magnitude of changes in current as loads are switched on. Electronic devices have initial current surges of a greater magnitude than the steady-state current. Turning on one load at a time (rather than switching on all loads simultaneously by throwing a master switch on a power outlet strip) reduces the initial current surge seen by the UPS and line conditioner. Since line conditioners have output voltage fluctuations during changes in rms load current, minimizing the initial current surges will minimize the fluctuation in load voltage.

There should also be a definite shutdown procedure. We again refer to the system shown in Fig. 102. The loads are turned off, one at a time, in the reverse order of the startup sequence. As a general rule, turn off the computer first, then each peripheral device. When all loads have been turned off, then switch the UPS off. Finally turn off the line conditioner.

ZONES OF PROTECTION

All parts of the computer system should be powered from the same line conditioner and UPS when possible. This rule prevents damage and upset from differences of ground potential between interconnected items.

Often it is not possible to operate the entire system from a single line conditioner. For example, clusters of desktop computers located in various rooms may share the same peripheral (e.g., printer or plotter). In this situation two rules apply.

1. All of the equipment should be connected to the same level of mains protection. For example, if one device is connected to a line conditioner, then all of the other devices should be connected to a line conditioner too. The number of line conditioners that are required depends on the location of the equipment.

2. All of the data lines between equipment that is connected to different line conditioners should contain protection against overvoltages. Protective circuits should be installed at both ends of each cable. Every wire in the cable, including unused wires, should be connected to a protective device. Otherwise sparks could form between an unused wire and a wire that is connected to the equipment.

An example of a distributed system is illustrated in Fig. 103, where the bold lines indicate cables that supply electrical power to the equipment. For simplicity, the varistors upstream from each line conditioner are not shown. The line conditioners that are connected to two or more loads should also have varistors connected to the output of the conditioner or in an outlet strip that services the loads. Narrow lines indicate data cables, for example, RS-232 protocol.

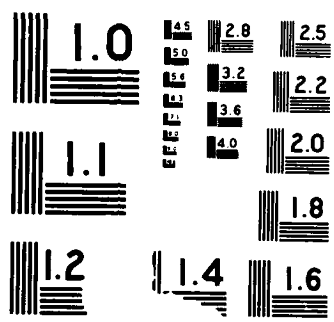
Protective devices are shown on each end of cables that go away from the region served by each line conditioner. There is no need for protective devices on the cable between the computer and the printer, since both are connected to the same line conditioner.

Suitable protective devices are described in Reference 1.

All telephone lines that are connected directly to a modem (i.e., not through an acoustic coupler) should have protective devices. Common telephone installations have a spark gap protector (either a sealed gas tube or a carbon block gap) near the point of entry. Additional protective devices may be necessary to prevent damage to the modem, computer, and terminals. Such devices are beyond the scope of this report.

AD-A192 582 MITIGATION OF MAINS DISTURBANCES(U) PENNSYLVANIA STATE 3/3
UNIV UNIVERSITY PARK R STANDLER ET AL NOV 87
AFWL-TR-86-80 F29601-85-K-0035

UNCLASSIFIED F/G 10/2 NL


1.0
4.5
5.0
5.6
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.2
1.4
1.6

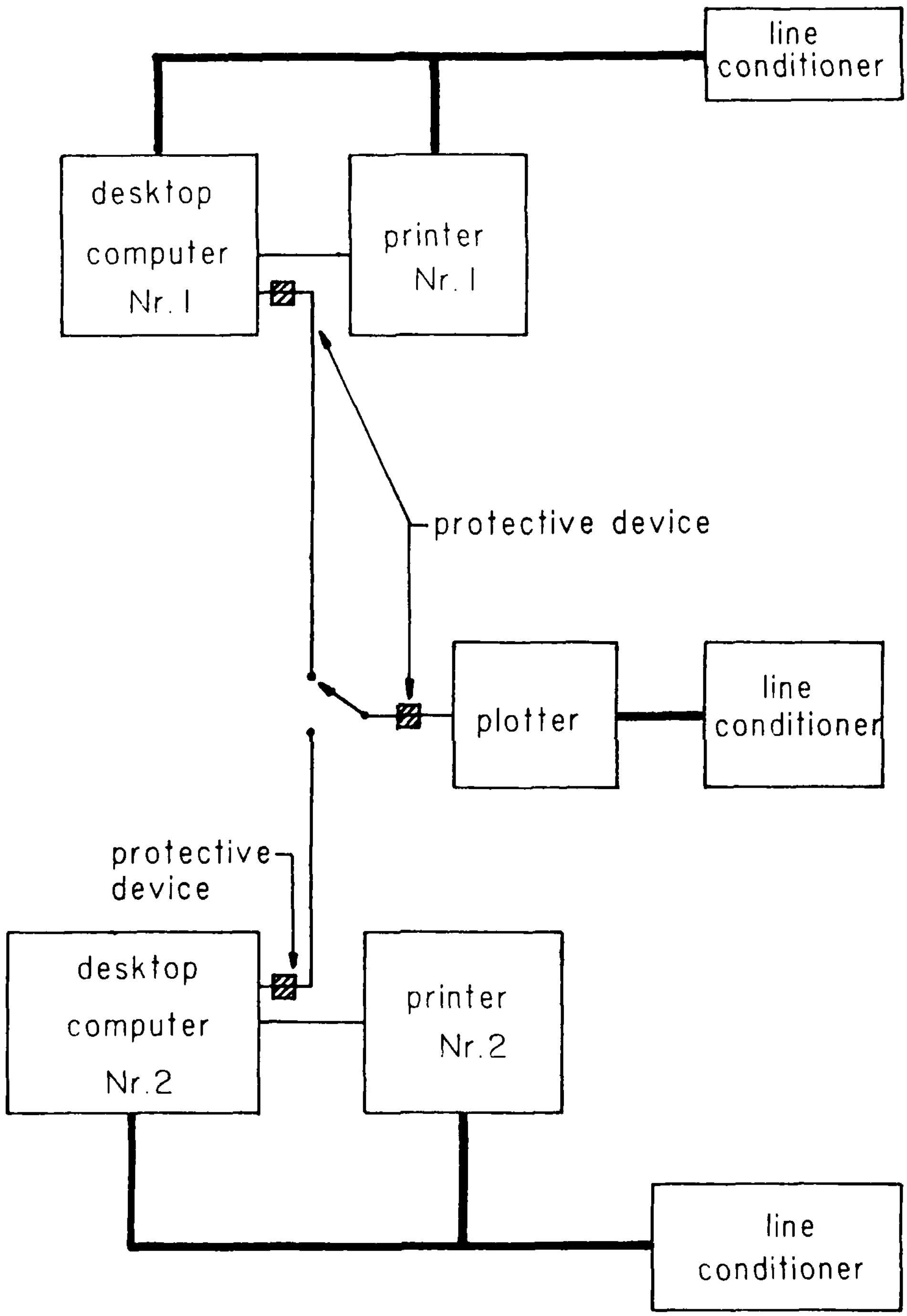


Figure 103. Distributed system.

CONCLUSION

There are many choices and compromises to be made when specifying power conditioning equipment for critical electronic systems. The basic decisions can be condensed to the following three rules.

1. All critical or expensive electronic systems should be protected from damage by high voltage transients. Metal oxide varistors are recommended for this purpose. Varistors are desirable even if line conditioners or other isolating devices are used.

2. Computer users who would be seriously inconvenienced by computer errors caused by fluctuations in rms voltage should purchase a line conditioner. Varistors should be connected upstream from the line conditioner.

3. If continuous operation is essential, then a UPS should be purchased. One can purchase either a line conditioner and a standby UPS or a true UPS in order to obtain reasonably complete protection.

REFERENCES

1. Standler, R. B., Transient Protection of Electronic Circuits, AFWL-TR-85-34, Air Force Weapons Laboratory, Kirtland AFB, NM, August 1984.

2. Duell, Arthur H., and W. Vincent Roland, "Power Line Disturbances and Their Effect on Computer Design and Performance," Hewlett-Packard Journal, 32, 1981, pp. 25-32.

3. Goldstein, M., and P. Speranza, "The Quality of U.S. Commercial AC Power," IEEE Intelec Conference Proceedings, 1982, pp. 28-33.

4. Key, Thomas S., "Diagnosing Power Quality-Related Computer Problems," IEEE Trans. on Industry Applications, Vol. 15, No. 4, July -Aug. 1979, pp. 381-393.

5. Speranza, Paul D., "A Look at the Quality of AC Power Serving the Bell System," Bell Laboratories Record, 60, July 1982, pp. 148-152.

6. Kania, Michael J., Robert F. Piasecki, Douglas R. Sewart, Sahin Danis, "Protected Power for Computer Systems," Western Electric Engineer, Vol. 24, No. 2, Spring-Summer 1980, pp. 40-47.

7. Martzloff, F. D., and G. J. Hahn, "Surge Voltages in Residential and Industrial Power Circuits," IEEE Trans. on Power Apparatus and Systems, Vol. 89, No. 6, July-Aug. 1970, pp. 1049-1056.

8. Allen, G. W., and D. Segall, "Monitoring of Computer Installations for Power Line Disturbances," IEEE Power Engineering Society Winter Meeting Proceedings, Paper 199-6, Jan. 1974.

9. Allen, George W., "Design of Power-Line Monitoring Equipment," IEEE Trans. on Power Apparatus and Systems, Vol. 90, No. 6, July-Dec. 1971, pp. 2604-2609.

10. Martzloff, F. D., "Propagation and Attenuation of Surge Voltages and Surge Currents in Low-Voltage AC Circuits," IEEE Trans. on Power Apparatus and Systems, Vol. 102, No. 5, May 1983, pp. 1163-1170.

11. Sola, J. G., "Constant Potential Transformer," U. S. Patent 2,143,745. 10 Jan 1939.

12. Kimball, James D., "Static-Magnetic Regulators: Part I," Electronic Products, December 1966, pp. 58-63.

13. Kimball, James D., "Static-magnetic Regulators: Part II," Electronic Products, Vol. 9. No. 8, January 1967, pp. 74-75.

14. Lucarz, W., "An Old Solution to a New Problem," Electronic Products, Vol. 16, No. 4, 17 Sept 73, pp. 115-121.

15. Grossner, N. R., Transformers for Electronic Circuits, 2nd. ed., 467 pp., McGraw-Hill, New York, 1983.

16. Sola, J. G., "Transformer Having Constant and Harmonic Free Output Voltage," U. S. Patent 2,694,177. 9 Nov 1954.

17. Wroblewski, T., "Voltage Regulating Transformer," U. S. Patent 4,075,547. 21 Feb 1978.

18. Elliston, R. O., "High Speed Buck-boost Alternating Current Regulator," U. S. Patent 3,715,652. 6 Feb 1973.

☆ U.S. GOVERNMENT PRINTING OFFICE 1988 573 134/61,046

END
DATE
FILMED
6-88
DTIC